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DESIGN AND DEVELOPMENT OF A SEGMENTED MAGNET
HOMOPOLAR TORQUE CONVERTER

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Westinghouse Electric Corporation

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13 ABSTRACT

This program is for the research and development of a new mechanical power transmission concept: the segmented magnet homopolar torque converter. The purpose of this device is to convert unidirectional torque of constant speed (such as from a steam turbine prime mover) into variable speed output torque in either the forward or reverse directions. The concept offers an efficient, lightweight low volume design with potential application over a wide range of speeds and power ratings in the range from hundreds to tens of thousands of horsepower. This machine concept can be applied to commercial and military advanced concept vehicles for both terrain and marine environments.

The program places particular emphasis on the technology of liquid metal current collection systems for the reason this is essential for the success of the homopolar machine concept.

This report period encompasses the completion of Phase II experimental work and the initiation of Phase III. In Phase I the technical problems were reviewed, the machine concepts were studied, and a detailed technical plan was evolved for the entire program. In Phase II, theoretical, engineering, and experimental tasks were performed to develop a reliable constant speed current collection system which was demonstrated in an actual segmented magnet homopolar generator (SEGMAG). The objectives of Phase III are to extend the technology developed in Phase II for constant speed machines to the case of the torque converter which must operate at variable and reversing speeds, and then to construct and test a demonstration machine.

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| ship propulsion | | | | | | |
| torque converter | | | | | | |

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## SECTION 1

## INTRODUCTION AND SUMMARY

### 1.0 GENERAL

This is the fifth semi-annual technical report and covers the work performed from June 1, 1974 through November 30, 1974. During this period, the Phase II workscope was completed and Phase III was initiated in accordance with the agreed plan.

### 1.1 BACKGROUND

This program is for the research and development of a Westinghouse-proposed mechanical power transmission concept: the segmented magnet homopolar torque converter (SMHTC). The purpose of this device is to convert unidirectional torque of constant speed (such as from a steam turbine prime mover) into variable speed output torque in either the forward or reverse directions. The concept offers an efficient, light-weight low volume design with potential application over a wide range of speeds and power ratings in the range from hundreds to tens of thousands of horsepower. Initial analysis indicates that this machine concept can be applied to commercial and military advanced concept vehicles for both terrain and marine environments over a wide range of applications with considerable benefit to the U.S. Government, provided the complex current collection, liquid metal technology, and materials problems can be completely solved.

The present contract is part of a proposed three phase program to develop the segmented magnet homopolar torque converter (SMHTC). This program will: a) solve the operational problems relating to current collection systems for segmented magnet machines; b) demonstrate the solution of these problems in a small segmented magnet homopolar machine (SEGMAG); c) utilize the developed technology to design, construct and test a segmented magnet homopolar torque converter (SMHTC).

The program will place particular emphasis on the materials technology of liquid metal current collection systems for the reason that this is essential to the success of the homopolar machine concept for high power density applications.

### 1.2 OBJECTIVES

#### 1.2.1 Summary of Objectives

In Phase I, completed on January 9, 1973, all of the technical problems were reviewed, the machinery concepts studied, and a detailed technical plan was evolved for Phase II.

Phase II had the primary purpose of providing the necessary theoretical and engineering design work, as well as the supporting experimental tasks, to develop a reliable and efficient current collection system for the successful operation of a segmented magnet (SEGMAG) homopolar generator. Key task areas include: (a) the design, construction, and operation of a SEGMAG generator having sodium-potassium (NaK) current collectors and all necessary support systems for liquid metal handling and purification, cover gas purity maintenance, and shaft seals; and (b) the procurement and testing of a GEC Ltd. homopolar generator with its Gallium-Indium (GaIn) current collector system.

The objectives of Phase III are to extend the technology developed in Phase II for constant speed machines (such as generators) to the case of a torque converter which operates at low speed, zero speed, or reversing conditions, and then to construct and test a demonstration machine.

1.2.2  Summary of Technical Tasks

The technical subtasks for Phase I were described in detail in the first semi-annual technical report (E.M. 4471), and were as follows:

1) Segmented magnet homopolar torque converter (SMHTC) system studies.

2) Application study.

3) Liquid metal current collection systems.

4) Materials study.

5) Segmented magnet homopolar machine design.

6) Seal study.

7) Plan for phase II.

There were five major task areas under Phase II:

(1)  Machine Design and Testing

Construct a 3000 HP segmented magnet homopolar machine in order to prove the SEGMAG concept and to provide a test vehicle for the current collectors, seals, and materials which were developed under this program.

Obtain a homopolar generator from the General Electric Co. (GEC) of England in order to obtain operational experience with GaIn as a current collector liquid.

## (2) Application Studies

Select the most useful applications for segmented magnet homopolar machines or torque converters.

## (3) Current Collection Development

Evolve an effective liquid metal current collection system.

## (4) Liquid Metal Support Systems

Develop and fabricate liquid metal and cover gas recirculation systems to protect the liquid metal in the current collectors.

Study the compatibility of all machine materials (insulation, lubricants and structural materials) with the liquid metal current collection fluid.

Conduct a fundamental study of liquid metal technology, including surface wetting, aerosol formation, corrosion reactions, effect of high currents, and chemistry control in liquid metals.

## (5) Seal Study

Develop seal systems for unidirectional SEGMAG machines to: (a) confine the liquid metal to the collector zone; and (b) prevent air contamination of the liquid metal and loss of its protective cover gas atmosphere.

To implement the Phase III contructual workscope, the following task areas have been defined:

## (1) Machine Design and Testing

SEGMAG demonstration machine development and testing will continue, with the objective of further increasing output power and refining current collector technology.

GEC machine performance will be studied to evaluate GaIn current collection technology.

Torque converter. A conceptual design will be evolved for a prototype torque converter suitable for a military application.

## (2) Current Collection Development

The unidirectional SEGMAG current collectors of Phase II will be further refined and extended to higher speed applications. In addition, collectors suitable for reversible and variable speed applications will be developed. The work falls into five categories:

### 1.3.1.2 GEC Machine

During this period, installation of the auxiliary equipment was completed, and the GEC machine was successfully tested to verify its performance and to study its GaIn current collector system.

### 1.3.1.3 Torque Converter

A conceptual design is in preparation for an 8000 HP torque converter. This machine will be designed to accept input power from a gas turbine prime mover at 3600 rpm and deliver power to a propeller load at variable speeds to 500 rpm in either forward or reverse directions.

Electrical design studies were also initiated to develop optimum machine configurations for maximum efficiency and power density.

### 1.3.2 Application Studies

During this period the application of SEGMAG machines to propulsion systems for tanks and amphibious vehicles was investigated. In most cases the electric drive systems appear to offer many advantages, although detailed analysis of total system arrangement and performance is required to ascertain their feasibility.

### 1.3.3 Current Collection Development

During this report period, the initial tests of the SEGMAG generator have verified the suitability of the liquid metal current collector for use in homopolar machines of constant high speed (67 m/s collection). Studies have now been initiated to extend this technology to: 1) unidirectional high speed (96 m/s collector speed) generators; and, 2) torque converter and motor applications where reversible and variable speeds are encountered. This work is further described below.

### 1.3.3.1 SEGMAG Collectors

During the SEGMAG tests the hydrodynamic and eddy current drag, and ohmic power losses were determined for the collectors. In addition, the operating characteristics of the liquid metal current collectors in regard to filling of the annulus and confinement or management of fluid spills within the generator were determined.

A few modifications to the current collectors are underway in order to increase the voltage and current output of SEGMAG, with retest scheduled for the next reporting period.

## 1.3.3.2  High Speed Collectors

Analyses of high speed current collector power losses as a function of rotational speed, collector rotor diameter, NaK fill level, etc. were performed.  Parametric variation illustrated the optimum collector geometry for most efficient machine performance.  Modifications to an existing test facility were planned, and a test program was developed to experimentally verify the selected variables for optimum high speed collector performance and characterization.

## 1.3.3.3  Flooded Collectors

A preliminary investigation was made of flooded current collectors for an 8000 HP disk-type homopolar machine (DISKMAG).  The greatest areas of concern are associated with power losses along the flat sides of the disks due to MHD effects, and excessive fluid pressure in the NaK with resulting thrust forces on the rotor and its bearings.  The studies are continuing.

## 1.3.3.4  Unflooded Collectors

Design objectives were established for the unflooded reversing collector, and potentially useful techniques were defined and outlined for use in the definition of new collector configurations.  Evaluation criteria have also been established to provide uniform screening of the proposed concepts.

## 1.3.3.5  Hybrid Collector

No work was scheduled for this reporting period.  A detailed study of the hybrid collector concept will begin in January 1975 and will include considerations of power losses, supporting liquid and gas flow systems, development of an optimum geometrical configuration, and problem area definition.

The hybrid current collector consists of a series of "floating pads" with perimeter seals, which contain liquid metal and utilize inherently small clearance with the rotor to minimize liquid metal leakage.

1.3.4  Liquid Metal Support Systems

Liquid metal support systems performance during the SEGMAG test program was satisfactory.  NaK loop, cover gas, material selections, coolant loops, instrumentation, and current collector performance were good.

A method of utilizing a single NaK recirculation and supply loop, for 20 or more current collectors is being analyzed.

A Ga-In technology review, including property, material compatibility, handling, maintenance, and decontamination and safety practices is being prepared.


1.3.5  Seal Studies

Shaft seal performance was monitored during the SEGMAG test program and verified the same good performance that was measured during the preliminary seal run-in period.  These SEGMAG shaft seals have thus been demonstrated to be suitable for use in machines of unidirectional rotation.

A state-of-the-art review was initiated to evaluate potential reversing seal concepts for the torque converter shaft seals.  They will be designed for low leakage and wear at operating speeds from zero to 500 rpm in either direction.

## SECTION 2
## MACHINERY

### 2.1 SEGMENTED MAGNET HOMOPOLAR MACHINE (SEGMAG)

#### 2.1.1 Objectives

The objective of this program is to demonstrate the SEGMAG concept and to provide a test vehicle for evaluation of the current collection systems, containment seals, and liquid metal handling systems developed in previous subassembly testing. The demonstration unit (rated 3000 HP, 3600 RPM) will subject the current collectors to current densities, leakage flux and other conditions associated with operation in a machine environment. In addition, the unit will provide for long-term testing of current collectors, their attendant support systems and the machine itself to develop operational data for liquid metal machines.

#### 2.1.2 Prior and Related Work

The SEGMAG concept was developed to provide a high performance DC machine without requiring superconducting magnet excitation. This low reluctance machine, using room temperature excitation, has capability for high output per unit weight and volume. The modular construction allows for higher outputs by using many modules connected in series. The characteristics of this machine have been investigated thoroughly in another U.S. Government Contract (N000 14-72-C-0393).

The demonstration SEGMAG machine design was completed in January 1974. Fabrication of the machine was completed in May 1974. The machine was assembled and installed on the test stand on May 24, 1974. Following connection of the subsystems, machine decontamination and system checkout, the machine technology test program was initiated. The initial portions of the test plan were executed successfully. These tests included slow speed rotor test to insure proper assembly and high speed machine test to develop the vibration signature of the SEGMAG. In addition, the machine friction and windage losses were determined as a function of machine speed.

#### 2.1.3 Current Progress

The initial series of SEGMAG tests were successfully concluded after 140 hours of operation. Output of 90,000 amperes at 19 volts was achieved. The testing has validated both the SEGMAG machine concept and the liquid metal current collector system.

As a current collector test vehicle, the performance of SEGMAG was excellent. The following objectives were accomplished:

- Techniques for filling the collectors were evaluated.

- Methods of detecting a filled collector were determined.

- High purity of both NaK and cover gas was maintained.

- Current collector filling was maintained, even in the presence of radial magnetic fields and high load currents.

- Liquid metal leakage from the current collectors was minimal except at the highest load current and highest open circuit excitation.

- The small NaK spillage that did occur was handled without difficulty, and without creating internal short circuits.

- Calculated viscous and eddy current losses were experimentally confirmed.

A few modifications to the current collectors and machine have been made in order to increase voltage and current output, with retest scheduled for the next reporting period.

The SEGMAG machine is shown assembled in Fig. 2.1.1 and in its test stand in Fig. 2.1.2. After disassembly and modification the SEGMAG rotor, stator, and assembled machine are shown in Figs. 2.1.3, 2.1.4, 2.1.5 and 2.1.6.

2.1.3.1 Detailed Progress Report

The performance tests on the SEGMAG were initiated in June 1974. Following the assembly sequence, cleanup sequence and low and high speed rotor tests, operational tests with NaK were performed.

The initial tests consisted of injecting NaK into each collector at zero speed to develop operating procedures for the NaK supply loops. Some loop plugging was encountered during these tests. Investigation showed that the inlet temperature to the machine was too low causing precipitation of NaK oxides leading to inlet plugging. The plugs were removed from the machine inlet and testing was continued. All NaK supply lines were operated successfully for an extended period following stabilization to insure that all oxides were removed from the lines and the machine internals.

Following successful conclusion of the zero speed NaK supply system tests, the collectors were operated with the rotor rotating to develop filling, operational and withdrawal procedures for the system. Each
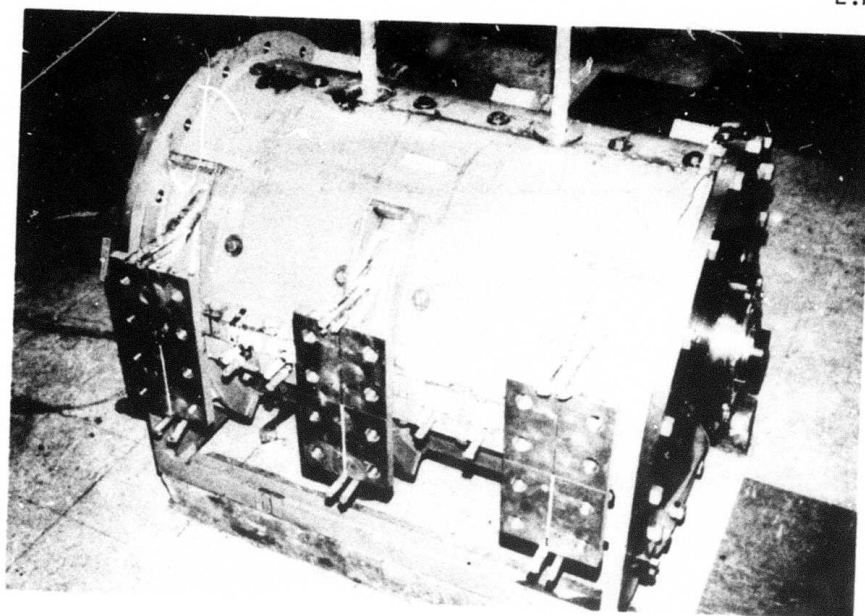
Fig. 2.1.1: SEGMAG Generator - The current collector terminals are shown in the foreground. The leads to the excitation coils are on top.
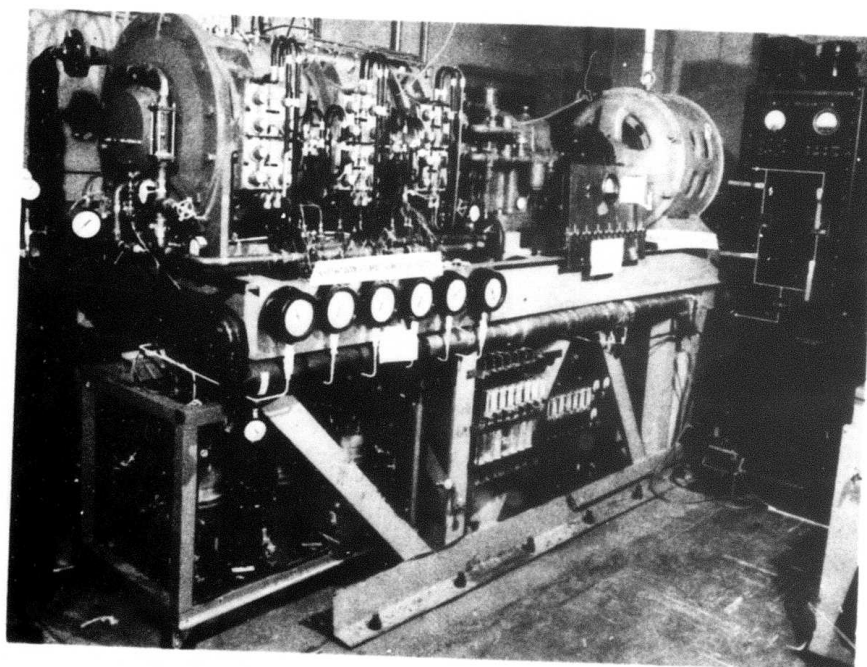


Fig. 2.1.2: SEGMAG Generator on its test stand - The drive system and gas purification system are both on the right. The six NaK purification and supply loops are below. To their right are the gas subsystems for intercollector pressure balancing and shaft sealing.
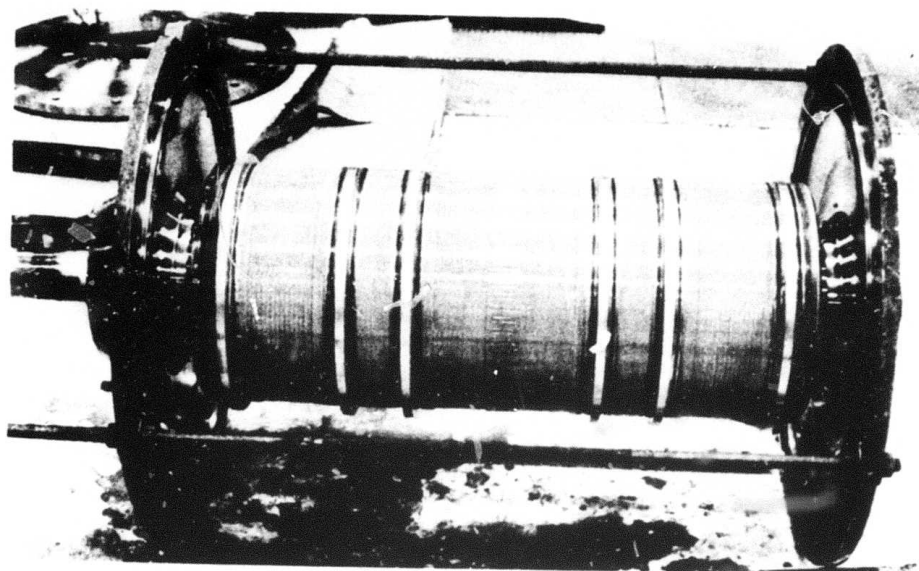
Fig. 2.1.3:  SEGMAG rotor and end bells



Fig. 2.1.4:  SEGMAG stator half

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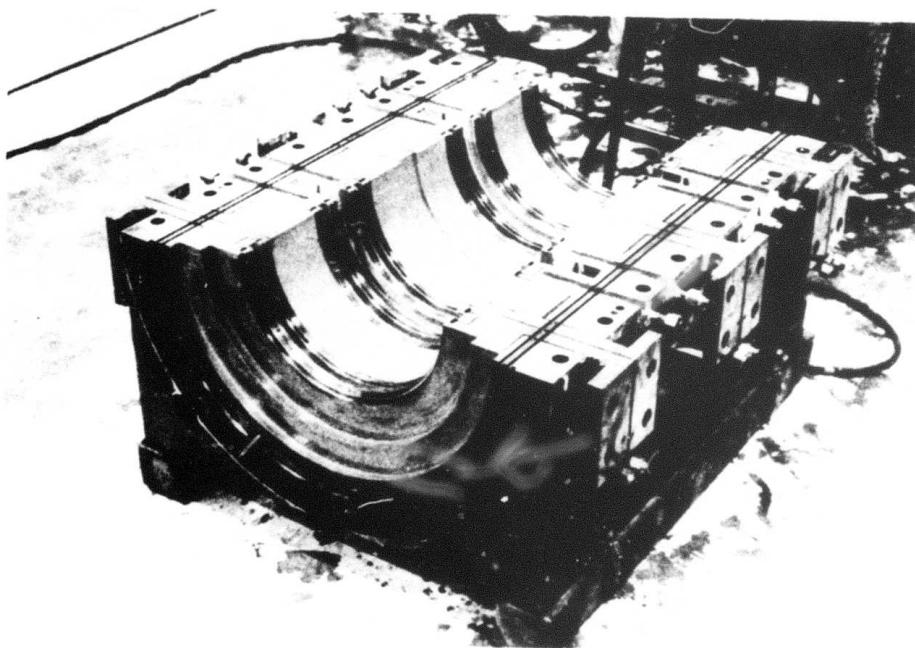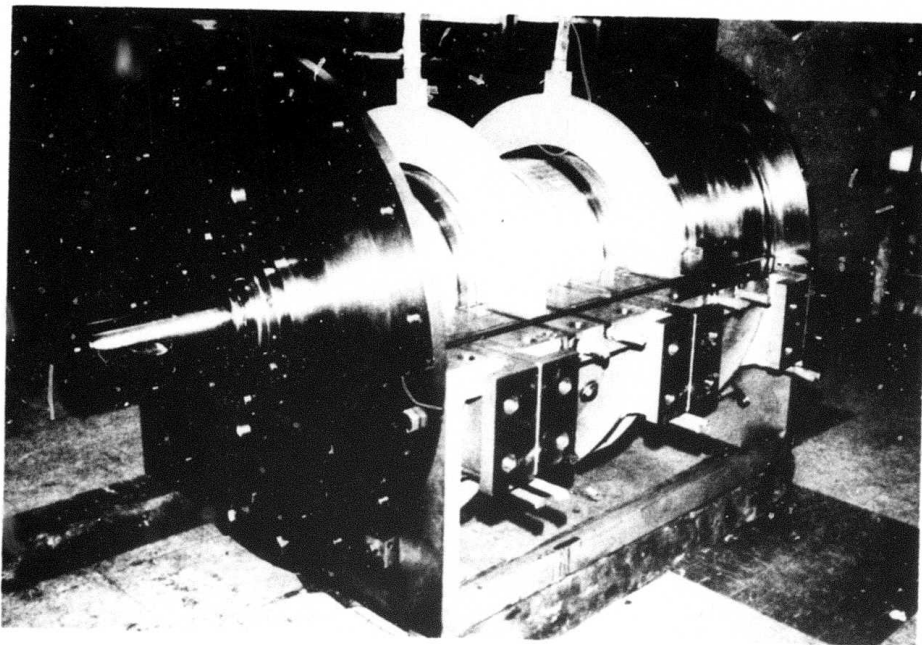
Fig. 2.1.5: SEGMAG with top half of stator removed, showing field excitation coils
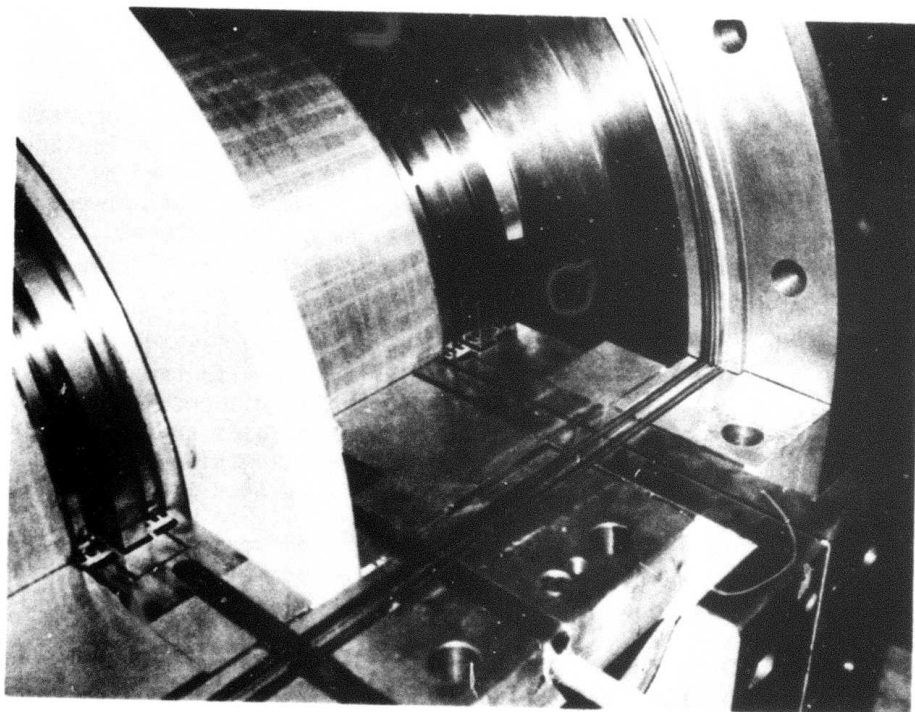


Fig. 2.1.6: Closeup of Fig. 2.1.5 showing SEGMAG current collector detail

collector was filled, operated and drained individually. The
filled collectors were operated at various speeds to the design speed
of 3600 rpm to determine the current collector viscous losses as a
function of speed. These losses, described in detail in Section 5.0,
were similar in magnitude to those measured on the current collection
test stand. Losses were determined by measuring the power input to
the test stand drive motor and subtracting previously measured
machine friction and windage losses. The accuracy of these measurements
was not as good as the measurements in the current collector test
stand since the viscous losses of one collector were insignificant
in comparison to the test stand and machine friction and windage
losses.

The next series of tests entailed operation of the machine with all
current collectors filled. The purpose of this test was to:

- Develop operating procedures for SEGMAG with all
  collectors filled.

- Develop shutdown procedures from a condition of full
  speed operation.

- Measure viscous losses of the machine with all collectors
  functioning.

- Develop operational procedures of the test stand, SEGMAG
  and all support systems with all collectors filled.

The tests showed that all collectors could be filled and operated
successfully at various machine speeds with little or no leakage
from the collector area. Collector leakage was measured by collecting
NaK that had accumulated in the machine drains located between collectors.
Although little or no leakage was measured during extended constant
speed runs, some leakage was detected during machine startup and initial
current collector filling. As operating procedures were finalized
and as personnel became familiar with the operating characteristics
of the machine and support system, the collector leakage decreased
during transient operation such as filling and withdrawal. When exces-
sive leakage from the current collector zones was encountered,
intermittant shorts were developed between modules and between modules
and ground. These shorts were caused by an excessive accumulation of
NaK in the machine drains which were not insulated module to module or
module to ground. These shorts could generally be cleared by draining
the NaK from the machine drains. The machine drains were not designed
to accommodate the transient collector leakage of 5-10 cc encountered
during this portion of the test plan.

The next section of the test plan entailed short circuit testing of the
center module. For this test, short circuiting shunts were installed
on the leads of the center module. The eight shunts, each designed for

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12,500 amps, had been previously calibrated with a 1000 amp power supply. Each shunt was instrumented to measure the shunt millivolt drop and shunt temperature. The center module leads were cleaned and polished and the shunt contact faces were silver plated prior to installation to minimize contact resistance. Each shunt mounting bolt was torqued to 75 ft-lbs to insure uniform contact of all eight pieces. A stable 30 amp power supply was connected to the excitation coils for the short circuit tests. The center module current collectors were filled and the machine speed was increased to 3600 rpm and the losses measured prior to the test. The field excitation was increased in two steps, one at 20,000 amp machine current and one at 40,000 amp machine current and the machine parameters were recorded. While operating at 40,000 amperes and 3600 rpm, the machine seized and was disassembled, decontaminated and inspected to determine the causes of the seizure.

The seizure was caused by the apparent failure of a fiberglass reinforced resin band used to retain the center module rotor bars. The fiberglass protective can also failed in the center module. No damage was noted in the end modules. Upon removal of the debris, an inspection showed no mechanical damage to the rotor or stator.

A visual inspection revealed the need for additional electrical insulation in several areas including the auxiliary drains.

The lack of adequate insulation in these areas had apparently been the cause of intermittent module-module and module-ground shorting observed during the prior testing.

In addition a different rotor bar retention method was implemented, in which the iron of the rotor teeth was deformed into the copper bars at the axial center of the rotor.

Various epoxies were evaluated to improve the electrical insulation of the modules, on the basis of adherence and NaK compatibility. Acceptable materials and techniques for their application were found for each of the areas of concern, and the insulation system was appropriately upgraded.

In order to improve the performance of the current collectors, they were plated with 0.002 inches of silver, covered with a flash of gold. It was felt that this would facilitate wetting of the collector surfaces with NaK, based on the results of experiments done in a glove box.

A system for continuous blowdown and measurement of NaK collected in the auxiliary drains was installed. In addition, instrumentation was added to measure the "air gap" pressure differential between collectors.

Following the refurbishment program, the SEGMAG was returned to the test stand. Assembly and cleanup were completed by the end of August,

and the second test program was initiated. The low and high speed
rotor tests were run as before, including an overspeed test to 3950 RPM.
The machine vibrations were well within acceptable limits (less than
2 mils).

Procedures were developed to fill the collectors with NaK, and to
maintain the filled condition. The most successful technique was to
inject NaK at 600 RPM and then increase the speed to 3600 RPM. It
was necessary to preheat the collectors to 70°C to achieve filling,
confirming operational data developed on the current collector test stand.
The flow rates used were approximately 250 cc/min, a substantial increase
over those used in the previous test run. The viscous losses in the
collectors were found to be approximately 4 kilowatts per collector
at 3600 RPM, as predicted and demonstrated in the current collection
test stand.

The first electrical test was the open circuit test. The three
modules were connected in series, with fuses utilized between modules
for protection in the event of an accidental internal short circuit.
The fuses were never blown, indicating that the insulation which had
been applied was adequate to prevent such shorts. The voltage across
each module was monitored, in addition to the full machine voltage.

Two types of short circuit tests were performed. In the first, the
center module was shorted and the end modules left open. In the other
the end modules were shorted and the center module left open. All
three modules were not successfully tested simultaneously due to the
difficulty in canceling the residual magnetism in the three modules
using two excitation coils. Although a demagnetization of the machine
was attempted following the open circuit test, there was still suf-
ficient residual magnetism in the machine to circulate 50,000 to
100,000 amperes in the shorted condition. The extremely low internal
impedance of the SEGMAG requires an mmf equivalent to only a few hundred
ampere-turns to circulate these high currents. In the normal operating
condition for a SEGMAG machine, this problem would not occur because
the modules would be connected in series.

The maximum current achieved in the center module was 90,000 amperes.
The end modules achieved 66,000 and 71,000 amperes. The current in the
machine was limited to 90,000 amperes since evidence of NaK expulsion
due to load current was noted at that point. Only the center module
was pushed to the current collector limit, and it is expected that the
end modules are both capable of carrying the same current as the center
module.

Following the test run the machine was disassembled and inspected.
Decontamination was rapid and straightforward.

Several modifications were made including:

- Insulation in the collector region to improve NaK containment.

- A strain gauge system on the rotor shaft to improve torque and power measurements.

- Changes in the air gap configuration to improve the machine performance.

The machine is being reinstalled in the test stand for open and short circuit performance testing.

## 2.2  GEC GENERATOR

### 2.2.1  Objectives

The General Electric Company, Ltd., of England has developed an experimental homopolar generator which utilizes a GaIn current collection system. This generator employs an electrochemical purification system to maintain the purity of the liquid metal and avoid the "black powder" problems of previous investigators who used this metal. ARPA has approved purchase of this generator for experimental evaluation under the contract. The machine will be used to provide operating and technical experience with GaIn as a current collector liquid and to supplement the main experimental studies which will be conducted with NaK. This experience is expected to be valuable in broadening the scope of the program beyond the alkali metals. The physical design of the machine and its performance will be investigated thoroughly, and the unit may also be employed as a high current dc source in the current collector test program.

### 2.2.2  Prior and Related Work

Liquid metal current collection systems have a high potential to function efficiently with long, trouble free life in the face of high electrical current loads and high rotational speeds conceived for homopolar machines of the advanced segmented magnet design.

Based on extensive study, NaK-78 was selected as the best liquid metal for current collectors employed in the SEGMAG machine, and GaIn was selected as the alternate choice.

Since GaIn has been identified as the back-up choice to NaK, the ability to work with and study a functioning GaIn unit is expected to be highly instructional in the general sense and also to shorten any subsequent development effort with GaIn.

Based on an extensive search of the market we have concluded that the GEC machine is the best vehicle to provide the GaIn experience needed for this program. No other liquid metal machine in the world, to our knowledge has operated continuously longer than 40 hrs without maintenance. Therefore, this machine, which has operated up to 1000 hours with no problems, represents a unique development.

The GEC generator is a vertical shaft machine utilizing GaIn liquid metal eutectic as the slip ring contactor. The generator is rated at 16,000 amperes, 8 volts when driven at 3400-3600 rpm. Figure 2.2.1 displays schematically the GEC generator vertical shaft concept.

During Phase II, the acceptance tests were successfully performed in England at The General Electric Company, Ltd., and witnessed by Westinghouse personnel. These tests consisted of open circuit, short circuit, generator load, motor and an endurance test. The proper operation and maintenance of the unit were also demonstrated.

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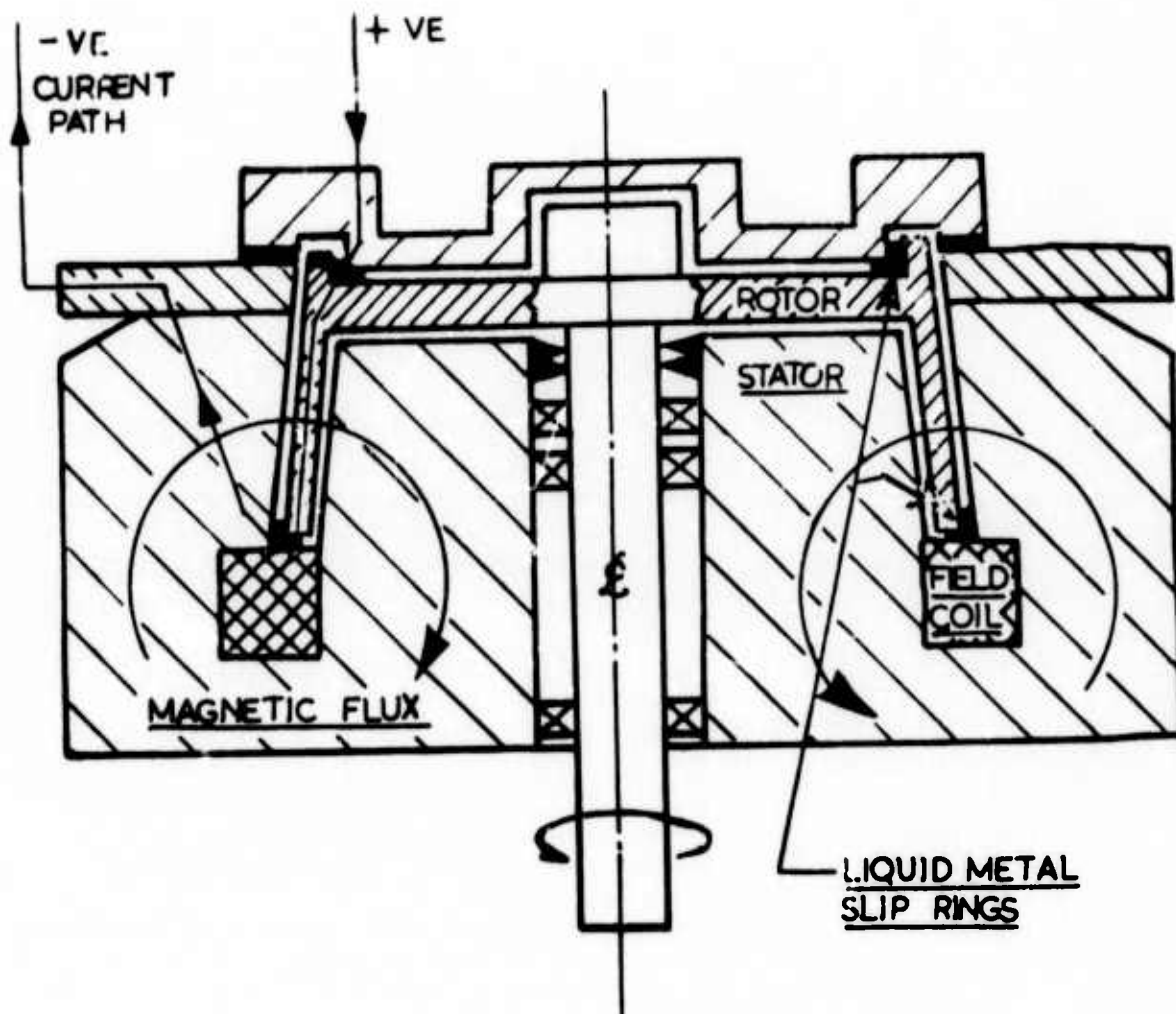


Fig. 2.2.1: GEC vertical shaft homopolar machine schematic

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The GaIn purification cell was severely damaged in shipment. A replacement cell was fabricated by Westinghouse using detailed drawings furnished by GEC Company.

The GEC generator test stand was completed in Phase II, and the machine was installed. The test stand is powered by a 50 HP 1750 rpm AC machine, and a drive train provides speeds of 1800 and 3600 rpm.

## 2.2.3 Current Progress

During this period, installation of the auxiliary equipment was completed, including cover gas, cooling water, and instrumentation. The GEC machine was then successfully tested to verify its performance and to study the GaIn current collector system.

Figures 2.2.2 and 2.2.3 are photographs of the GEC test area located in the Westinghouse Liquid Metals Laboratory.

The following are the four basic tests performed on the GEC machine:

1) An open circuit test, to determine no-load voltage and current collection magneto-hydrodynamic losses as a function of field current.

2) A machine short circuit test, to determine the $I^2R$ losses in the machine.

3) A motor test, to measure the vibration levels, magnetohydrodynamic losses, and coastdown time.

4) An endurance test, to confirm the performance capability of the machine and its auxiliaries over a long time period. Liquid metal loss rate, cell performance, argon contamination and seal performance were monitored.

## 2.2.3.1 Open-Circuit Test

The machine was installed in the test stand with the output leads open circuited and purged with dry argon for four days prior to the test. The cover gas was maintained at a pressure of 1 cm Hg with a flow of 50 cc/min. A GaIn charge of 80 cc with 380 cc of 3M NaOH was supplied to the purification cell. The moisture of the effluent gas measured approximately 100 ppm at the start of the tests.

The machine was tested at 1800 and 3600 rpm with field excitation currents of 0.0, 1.5, 3.0 and 5.0 amps. During the test, the GaIn pump was switched off to determine losses at zero liquid metal flow.
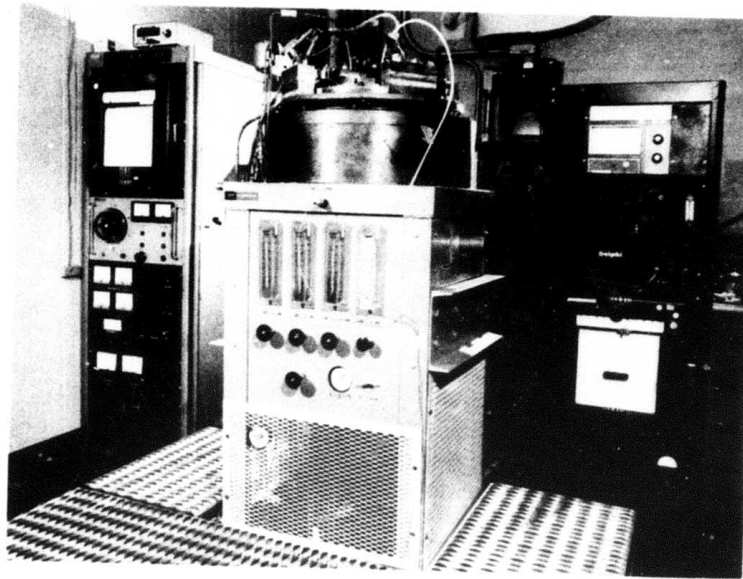
Fig. 2.2.2: Front view of GEC test area in the Westinghouse Liquid Metal Laboratory. The cover gas impurity monitoring system is on the right. The machine control and test panel is on the left. Below the machine is a cover gas flowmeter, and also flowmeters and pressure regulator for the cooling water system.
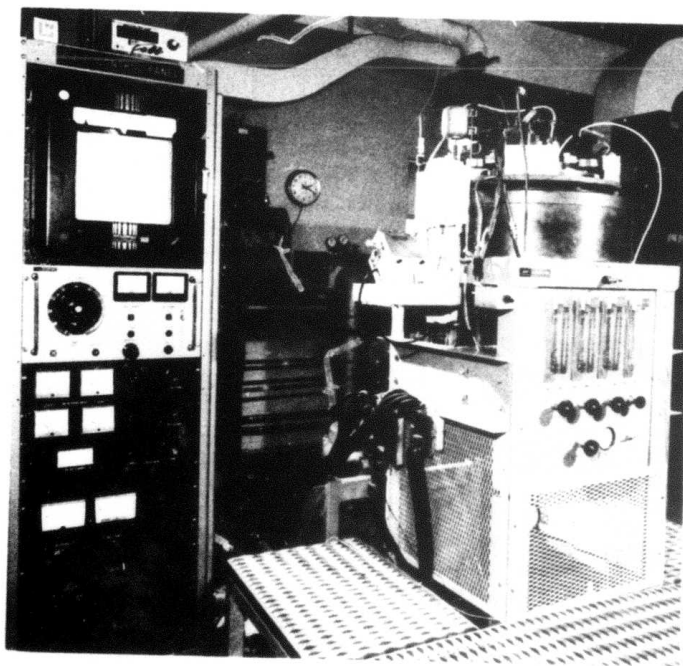


Fig. 2.2.3: Side view of the test area showing the GaIn electrolytic purification cell, to the left of the GEC machine.

2-13

The test results were evaluated to determine the losses as a function of speed and excitation. The results of open circuit tests are shown in Fig. 2.2.4. As expected the losses increased with machine speed. The effect of excitation on losses was not present until a speed of 3000 rpm was achieved. The losses increased with field at this speed.

Figure 2.2.5 presents the total flux calculated from the generated open circuit volts and speed.

### 2.2.3.2  Short Circuit Test

The machine leads were short circuited with calibrated shunts to measure the current. The shunt temperature was monitored to provide a thermal correction for shunt temperature. The machine was operated at 1800 and 3600 rpm and the level of excitation was adjusted in order to provide short circuit currents up to 52 kiloamperes. The test data taken is presented in Fig. 2.2.6.

During the short circuit test program a high level of vibration was encountered in the test stand and was determined to be caused by the bearings and the machine support assembly. The vibration was reduced to acceptable levels by making the support assembly more rigid in order to maintain better alignment, and by installing new bearings.

The short circuit performance test showed that a maximum of 52 kiloamperes, is achievable, which is more than three times the rated 16,000 amperes. Above this limiting value the liquid metal could be forced out of the collectors, with consequent loss of output voltage and current.

During the short circuit test program, the GaIn flow was blocked by the formation of black gallium oxide powder. This resulted in overheating of the lower current collector area with consequent reduction in output current. The blockage was removed by reaming the liquid metal drain line, and purging the machine with argon gas. This procedure permitted the short-circuit test program to be satisfactorily completed. However, the machine internals will be more thoroughly examined and cleaned during the next reporting period.

### 2.2.3.3  Motor Test

For the motor test, the machine was operated at various armature currents, field excitation currents and machine speeds to determine machine vibration, magnetohydrodynamic losses and machine coastdown time. The data taken during the motor test is presented in Fig. 2.2.7, which shows that input power and accordingly the machine hydrodynamic losses are a strong function of speed.
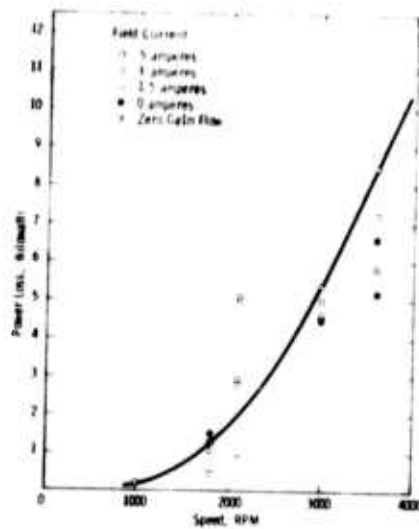
Fig. 2.2.4: GEC open circuit test losses
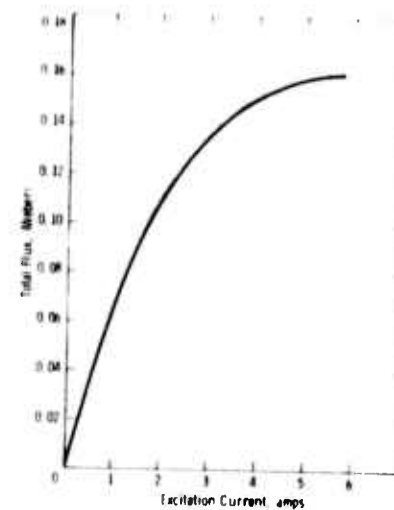


Fig. 2.2.5: GEC total flux calculated from open circuit voltage and speed
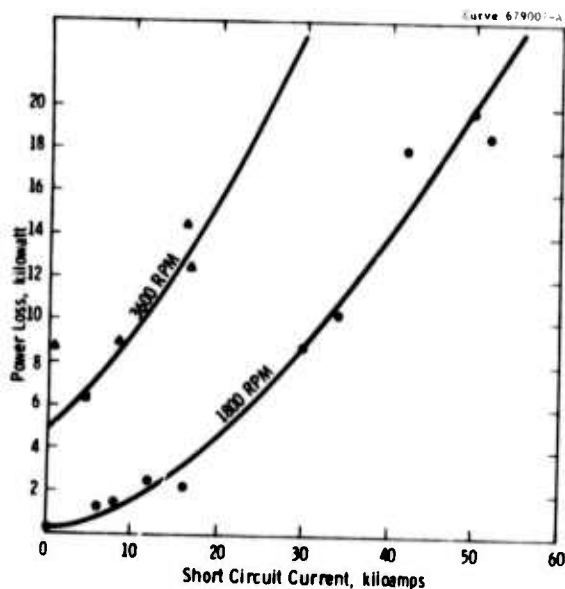


Fig. 2.2.6: GEC short circuit test losses
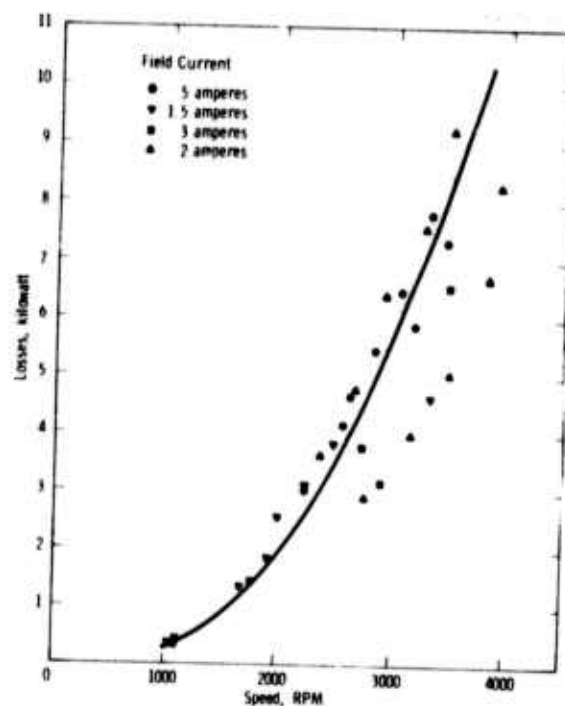


Fig. 2.2.7: GEC motor test losses

2-15

The motor was started from rest by applying a voltage to the output leads after injecting some liquid metal prior to hand rotation. Sufficient GaIn was retained in the collector to carry the current required for machine acceleration.

### 2.2.3.4 Endurance Test

The endurance test was performed with the machine operating as a motor for two hours at approximately 3000 rpm. All machine temperatures held constant and there was no evidence of abnormal operation.

### 2.2.3.5 Machine Performance

The test results have enabled the machine losses to be segregated into three categories:

- Machine friction and windage losses with GaIn in the collector.

- MHD losses due to leakage flux in the current collector.

- Joule heating losses due to current flow in the machine.

The viscous, friction and windage losses were determined at various speeds and zero excitation by measuring the input power to the coupled drive motor. The difference between this power and the uncoupled drive motor losses at each speed determined the generator losses. These viscous, friction and windage losses are shown in Fig. 2.2.8 as a function of speed. The friction and windage losses cannot be separated from the liquid metal viscous losses because gallium indium could not be completely excluded from the collector areas during the test to measure friction and windage losses. The reason was that GaIn was electroplated onto the rotor and stator prior to assembly to insure adequate wetting and this caused GaIn liquid to adhere to the collector surfaces.

The MHD losses were determined during open circuit tests at various speeds and field currents. These power losses are shown in Fig. 2.2.9 as a function of speed and field excitation. The power losses increased with speed due to viscous losses, and with excitation due to the inter- action of leakage flux with currents induced in the liquid metal of the collector. These currents induced by the leakage flux resulted in losses that became significant at higher speeds and excitation levels.

The $I^2R$ losses were determined by the short circuit tests. The sum of friction, windage and viscous losses were subtracted from the power losses measured during short circuit to determine joule heating losses in the machine. The MHD losses were neglected because of the low machine flux during short circuit. These losses are shown in Fig. 2.2.10 as a function of machine current and speed.
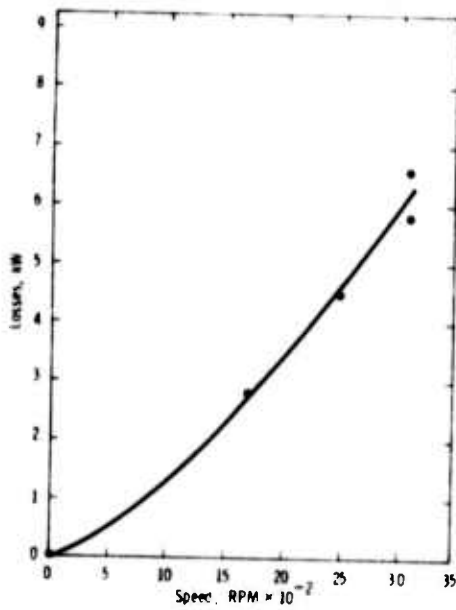
Fig. 2.2.8: GEC calculated losses due to friction, windage, and liquid metal viscosity.
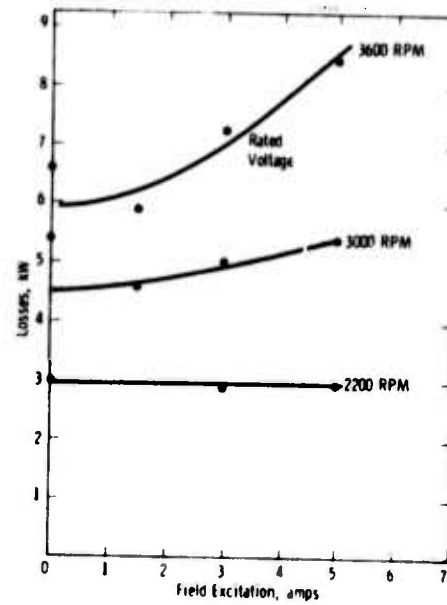


Fig. 2.2.9: GEC calculated MHD losses.
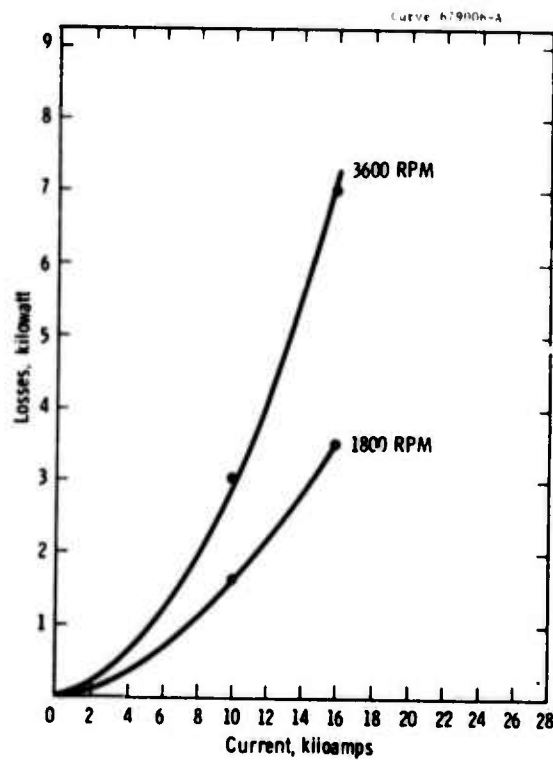


Fig. 2.2.10: GEC calculated $I^2R$ losses

The losses measured during the test program at 3600 rpm are:

| | |
|---|---|
| Viscous, friction, windage | 6.2 KW |
| MHD | 1.0 KW |
| $I^2R$ | 7.0 KW |
| Total losses | 14.2 KW |

For the 100 KW GEC machine the overall calculated machine efficiency was 85.8%. At lower speeds the efficiency rises to a level approaching 94%.

2.2.3.6    GaIn Purification Cell

The gallium indium liquid metal was purified by an electrolytic regeneration cell that is shown schematically in Fig. 2.2.11.

The cell was provided with 3M NaOH as the electrolyte and was operated from a 2A. 5V d.c. supply connected into a terminal block on the side of the frame. It was essential that the polarity be positive for the wire electrode and negative for the liquid metal.

A stirrer was provided to increase the regeneration rate of the cell in the event of an abnormal amount of compound entering the cell (e.g., after storage). The stirrer was not normally used during running as only small quantities of compound were generated.

Precautions were taken to insure a clean, non-reactive cover gas atmosphere inside the machine to minimize the oxidation of Ga. The machine was purged with high purity argon prior to startup. Cover gas pressure was maintained at 1-2 cm Hg and at a flow of 50-100 cc/min. During the prestart degas cycle, the excitation current was turned on to warm the housing and assist in outgassing the machine internals as well as to maintain the GaIn in the liquid state. The effluent purge gas contained a typical level of 100 ppm(v) moisture at the time of machine startup. The GaIn electrolytic purification cell functioned properly during all the machine tests and only required stirring under the heaviest load conditions. GaIn flow rates were in the 30 cc/min range.

Effluent cover gas impurity levels rose appreciably during machine power tests, but did not cause any problem. For instance, gas chromatograph readings were taken during the endurance test and indicated that oxygen levels in the effluent gas remainted below 15 ppm (detection level) throughout the test. However nitrogen and hydrogen levels rose appreciably at the higher power levels, yet remained below 2000 (.2%) and 8000 (.8%) ppm respectively. These impurities and the high gas moisture content could have been the result of carry over from the 3M NaOH cover fluid in the GaIn purification cell.

The endurance test required high performance from the GaIn purification cell. The white, cloudy sodium hydroxide became grey, and black particulates were observed in the solution. The stirrer was applied, and considerable bubble generation at the GaIn pool surface occurred. The particulates were dark brown to black in color, sponge-like in appearance, and varied in size up to 3/16 inch in diameter. The stirring action broke the large particles, and continual stirring after machine shutdown reduced the particle density as the Ga oxides were reconverted to Ga.

Vent

From Machine →

Electrolyte

Liquid Metal

To Machine
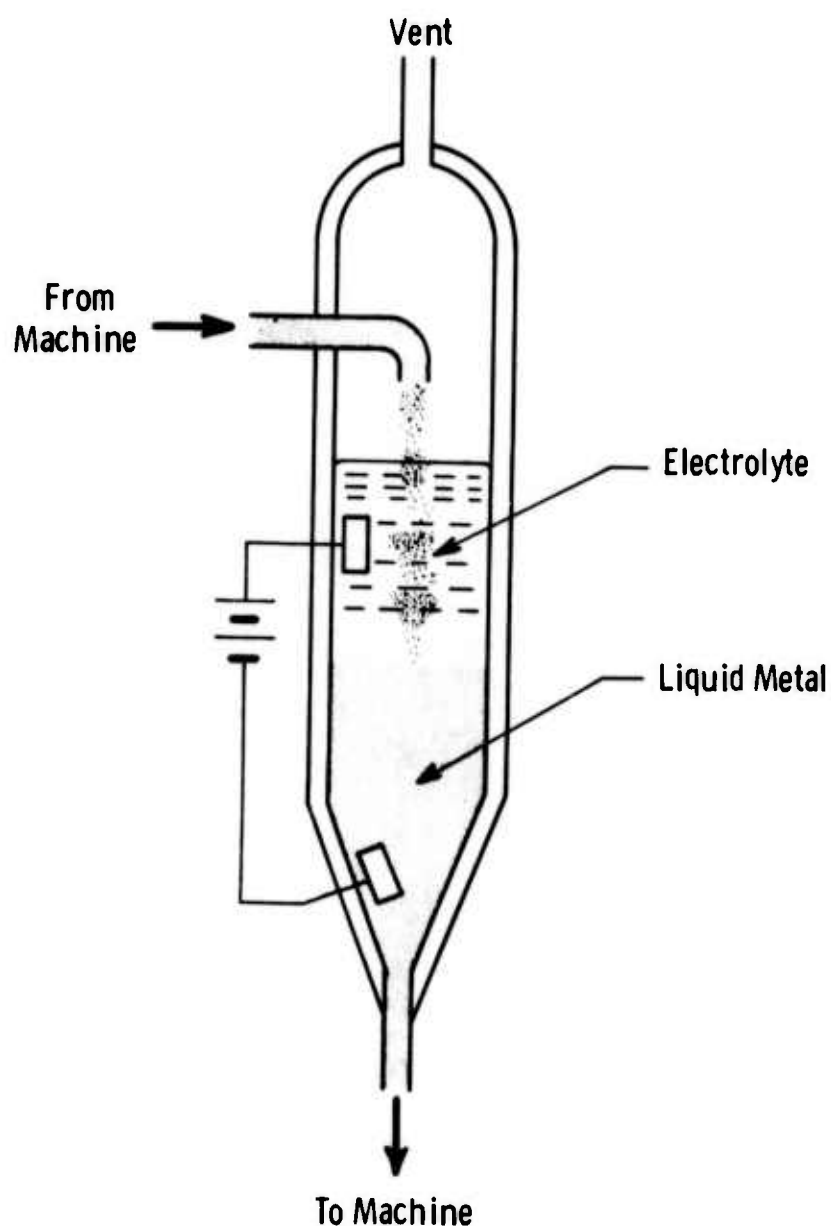
Fig. 2.2.11: GaIn purification cell schematic

### 2.3 SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER (SMHTC)

#### 2.3.1 Objectives

The objective of this program is to investigate the segmented magnet homopolar torque converter (SMHTC), within the framework of some of the more promising applications. This concept will then be demonstrated in a torque converter producing 8000 HP at 500 rpm from a 3600 rpm drive unit. The output shaft shall deliver constant torque from zero to 500 rpm in forward and reverse rotation. The concepts demonstrated in this machine will be extrapolatable to larger units.

Our objective in Phase I was to study the various configurations proposed for the SMHTC, and the technical problems involved in developing the prototype machine.

In Phase III a conceptual design is to be evolved for the prototype torque converter.

#### 2.3.2 Prior and Related Work

The SMHTC concept was derived from a unique modular DC homopolar machine being investigated at Westinghouse. This machine, known as a segmented magnet homopolar machine (SEGMAG) uses series-connected DC modules to obtain the design output.

During Phase I of this contract, electrical analyses of large (30,000 HP) and small (6000 HP) machines were completed. The electrical analysis for the large unit was performed to determine the approximate size and weight for the unit. Two conceptual designs (radial and axial) were prepared for the 6000 HP machine.

The radial SMHTC design uses a SEGMAG generator mounted within a SEGMAG motor. The design uses a stationary stator located between the rotating drive shafts. The stator is separated magnetically to prevent interaction of the excitation from the motor and generator portions of the machine. A conceptual design layout for the radial design was prepared.

The axial design uses an inline SEGMAG generator and motor. This design is feasible if high current buses from the generator to the motor can be limited to approximately 12 inches. A conceptual design layout was prepared for this concept. A design study was initiated to develop alternate SMHTC concepts. The initial thrust of this study was to evaluate concepts for a reversing homopolar motor.

### 2.3.3 Current Progress

As reported in Section 3, our application studies have indicated that 8000 HP is a desirable rating of torque converter for the propulsion of various small Naval ships and boats. For this reason, the design goal for the prototype torque converter has been changed from 6000 HP to 8000 HP.

A conceptual design is being prepared for the 8000 HP torque converter. This machine will be designed to accept input power from a gas turbine prime mover at 3600 rpm and deliver power to a propeller load at variable speeds to 500 rpm in either forward or reverse directions.

Electrical design studies were initiated to develop optimum machine configurations for maximum efficiency and power density.

### 2.3.3.1 Typical 8000 hp Disk-type Motor Design (DISKMAG)

A number of designs for an 8000 hp disk-type "flooded gap" motor (DISKMAG) were considered during the study. The geometrical dimensions and operating conditions for a typical design are listed in Table 2.3.1, and illustrated in Fig. 2.3.1.

A qualitative description of the fluid flow behavior in a "flooded gap" motor is given in Section 4.2.3. The problem of fluid containment in the annular current collector gaps appears to be resolved by this machine concept. However, other problems associated with pressure and thrust loads placed on the machine seals and bearings, as well as power losses in the liquid metal, must be considered.

Unbalanced centrifugal pressures are induced in the liquid metal because of high velocity circumferential flow on one side of each disk and zero velocity on the other. Because of the required tandem arrangement, the unbalanced pressure created at each disk accumulates throughout the machine. If no axial circulation of fluid is allowed (as with a batch-loaded liquid metal system), the shaft seals and rotor bearings must withstand rather large pressures and thrust forces. On the other hand, if axial flow of liquid metal is permitted, such as under the action of the unbalanced centrifugal pressure, the fluid and mechanical loads on the seals and bearings will be reduced. This reduction is attributed to an electromagnetic pressure drop associated with movement of the conducting liquid metal in the machine's magnetic field. The following governing expressions which permit calculation of the machine seal and bearing pressures and forces have been developed by Rhodenizer and acknowledged in Section 4.2.3.

### TABLE 2.3.1

Dimension and Operating Conditions for a Typical
Design 8000 hp "Flooded Gap" Disk-Type (DISKMAG) Homopolar Motor

A. Operating Conditions

P = machine rated power, 8000 hp

I = machine full-load current, 100,000A

$B_{xi}$ = axial magnetic induction at inner collector, 0.25T

$B_{xo}$ = axial magnetic induction at outer collector, 0.35T

$B_{yi}$ = radial magnetic induction at inner collector, essentially zero

$B_{yo}$ = radial magnetic induction at outer collector, essentially zero

S = machine maximum speed, 8.33 r/s (500 r/m)

$\omega$ = rotor angular velocity, 52.36 rad/s

$B_x$ = axial magnetic induction in disks, 1.26T

B. Geometrical Design (rectangular cross-section)

$R_i$ = radius of inner collector, 0.161m (6.34 in.)

$R_o$ = radius of outer collector, 0.394m (15.507 in.)

$W_i$ = width of inner collector, $3.05 \times 10^{-2}$m (1.2 in.)

$W_o$ = width of outer collector, $3.05 \times 10^{-2}$m (1.2 in.)

$d_i$ = radial gap of inner collector, $1.65 \times 10^{-3}$m (0.065 in.)

$d_o$ = radial gap of outer collector, $1.65 \times 10^{-3}$m (0.065 in.)

N = number of disks, 14

G = axial gap between rotating and stationary disks, $3.05 \times 10^{-3}$m (0.12 in.)

C. Constants and NaK Physical Properties ($\sim$ 100°C)

$f(\delta<1)$ = Fanning friction factor, smooth surface, $0.7 \times 10^{-2}$

$f(\delta>1)$ = Fanning friction factor, roughened surface, $1.8 \times 10^{-2}$

$\rho$ = mass density, 850 kg/m$^3$

$\sigma$ = electrical conductivity, $2.2 \times 10^6$ mhos/m

$\varepsilon_k$ = specific contact potential (Cu-NaK-Cu), $4.1 \times 10^{-9}$Vm$^2$/A

$\eta$ = dynamic viscosity, $5.1 \times 10^{-4}$ N-s/m$^2$

Dwg 6252A32
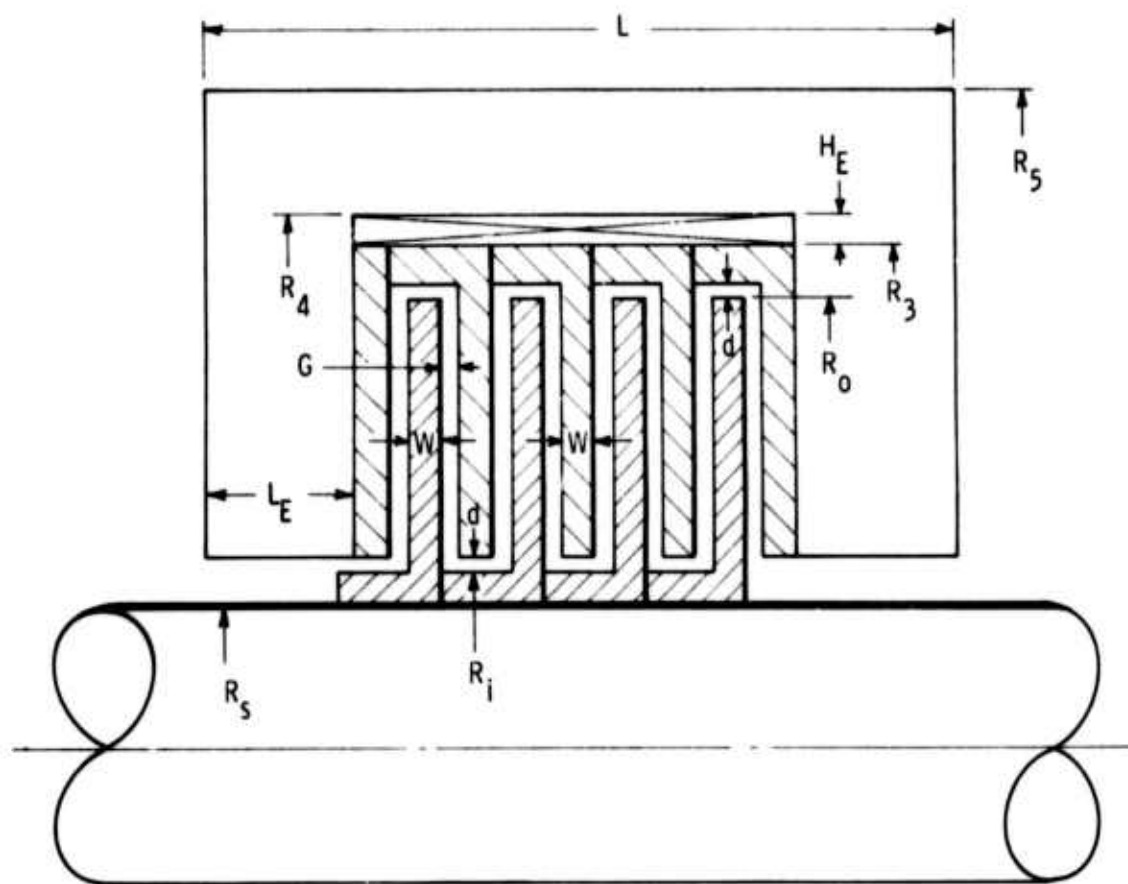


Fig. 2.3.1: Disk-type homopolar machine (DISKMAG)

Liquid metal <u>not</u> allowed to flow through the motor from end to end:

$$p_s = p_i + \frac{N\rho\omega^2}{2}(R_o^2 - R_i^2), \qquad (2.3.1)$$

where: $p_s$ = total pressure on seal, $N/m^2$

$p_i$ = liquid metal inlet pressure, $N/m^2$

$$F_R = \frac{N\rho\omega^2\pi}{4}(R_o^2 - R_i^2)^2, \qquad (2.3.2)$$

where: $F_R$ = rotor bearing thrust force, N

Liquid metal allowed to flow through the motor from end to end:

$$p_s = p_i + \underbrace{\frac{N\rho\omega^2}{2}(R_o^2 - R_i^2)}_{\substack{\text{Centrifugal} \\ \text{press.} \\ \text{rise}}} - \underbrace{(2N-1)\frac{B_x^2\sigma Q}{2\pi G} \ell n\left(\frac{R_o}{R_i}\right)}_{\substack{\text{Electromagnetic} \\ \text{press.} \\ \text{drop}}}, \qquad (2.3.3)$$

where $Q$ = liquid metal volume flow, $m^3/s$.

$$F_R = \frac{N\rho\omega^2\pi(R_o^2 - R_i^2)^2}{4} - \frac{(2N-1)B_x^2\sigma Q}{2G}\left[\frac{(R_o^2 - R_i^2)}{2} - R_i^2 \ell n\left(\frac{R_o}{R_i}\right)\right], \qquad (2.3.4)$$

Liquid metal allowed to flow through the motor from end to end under the action of unbalanced centrifugal pressure and neglecting fluid friction:

$$Q = \frac{N}{(2N-1)}\frac{\rho\omega^2 G\pi(R_o^2 - R_i^2)}{B_x^2 \sigma \ell n\left(\frac{R_o}{R_i}\right)}, \qquad (2.3.5)$$

$$p_s = p_i \qquad (2.3.6)$$

$$F_R = \frac{N\rho\omega^2\pi(R_o^2 - R_i^2)}{4}\left\{(R_o^2 - R_i^2)\left[1 - \frac{1}{\ell n\left(\frac{R_o}{R_i}\right)}\right] + 2R_i^2\right\}. \qquad (2.3.7)$$

For the 8000 hp DISKMAG motor under consideration, Table 2.3.2 shows the calculated values of pressure and thrust force which the shaft seals and rotor bearings must withstand under two of the above assumed conditions of liquid metal flow.

## TABLE 2.3.2

### Seal Pressure and Rotor Thrust Forces for a Typical 8000 hp Disk-type Motor (DISKMAG)

| Condition | Seal Pressure, $p_s$ | | Rotor Thrust, $F_R$ | |
|---|---|---|---|---|
| | $N/m^2$ | (psi) | N | (tons) |
| No liquid metal flow through motor | *2.11 x $10^6$ | *306 | 4.28 x $10^5$ | 48.1 |
| Liquid metal circulation by internal centrifugal pressure** | $p_i$ | $p_i$ | 1.21 x $10^5$ | 13.6 |

*pressure above inlet pressure, $p_i$

**max. NaK flow rate (assuming no friction), 4.79 x $10^{-4} m^3/s$ (7.6 gal/m)

As a result of the preliminary study, which included ranges in geometrical dimensions, load currents, and excitation levels, a number of problem areas associated with disk-type machines were found. A few of these concerns are summarized below.

- Complex construction of disks to obtain magnetic circuits with low axial and high circumferential reluctance.

- High machine power losses, attributed mainly to MHD effects in the axial gaps between disks (see section 4.2.3).

- Probability for turbulent rather than laminar flow and high short circuit losses in the liquid along the flat side walls of the machine disks. Reynolds to Hartman number ratios >1000 are calculated for operating conditions down to 30% of rated full load speed. Thus, the assumption of laminar fluid flow employed in the axial gap power loss expression is in doubt except at low speeds.

- A need is recognized for large thrust bearings and high pressure shaft seals to assure a fail safe machine design.

## SECTION 3
## APPLICATION STUDY

### 3.0 OBJECTIVES

Review and select promising applications for the segmented magnet homopolar machines and torque converters.

Several of the applications resulting from the Phase II application studies will be reviewed in conjunction with ARPA, and the most useful application will be selected.

### 3.1 PRIOR AND RELATED WORK

Previous Technical Reports discussed a number of applications which are potentially feasible. All of them were contingent upon proper solution of the current collection problem. The problem of using liquid metal to transmit simultaneously large quantities of electrical current and heat from the rotating armature must be solved in a reliable and safe fashion to realize these applications. In addition many applications require the collection of current at low speed and in both directions of rotation. Considerable progress on the hydraulic and dynamic aspects of the current collecting system has been made during Phase II of this study. The potential success of this current collection system provided encouragement to address the applications study. Prior studies revealed the advantages and disadvantages of segmented magnet homopolar machines in general and torque converters in particular.

Since one of the advantages of the SEGMAG machine is smaller size for a given capacity, an electric propulsion drive for a military tank was investigated. Electric drives for tanks have another advantage in that they provide a readily controlled independent tractive effort to each track over the entire speed range. The present system uses a hydraulic coupling and a gear unit which has the disadvantages of a fixed number of gear ratios and space constraints due to the mechanically interconnected components. The electric drive, on the other hand, permits smooth control of torque over the entire speed range. Historically, however, electric drives tended to be larger than mechanical drives due primarily to the required motor torque capacity at low speed.

### 3.2 CURRENT PROGRESS

#### 3.2.1 Tank Propulsion System

During this period, the investigation of utilizing SEGMAG machines for tank propulsion continued. In particular, the performance requirements of the XM-1 tank was analyzed.

Tractive effort (TE) basically sets the torque and volume of the drive motors. The maximum TE is specified normally as equal to the vehicle weight. The continuous TE or the point for which the transmission cooling system is rated occurs at a coefficient of friction .5 or 50% of the vehicle weight.

For a 60 Ton tank, the maximum TE is 120,000 lbs and the continuous rating is 60,000 lbs. Above 60,000 lbs the duration of the operation is a function of the thermal time constants of the transmission. On hard surface, the continuous rating point corresponds to operation on about a 50% slope. This, of course, is not a condition that exists for long periods in practice. However, extended periods of operation in clay or mud are encountered which require 1000 lbs of TE per ton of vehicle weight - the same loading condition.

The power of the present generation of tanks is selected on the basis of acceleration capability. This is in contrast to earlier criteria when the measure of performance was speed capability on steep grades.

Acceleration is the area of greatest concern. Although the vehicle has maximum TE capabilities of 2000 lbs/ton, during an acceleration from zero speed the torque transferred to the drive sprockets does not exceed about 500 lbs per ton.

The accelerating tractive effort is reduced by the ability to accelerate the engine under load and again by the energy required to accelerate the rotating parts of the drive.

Therefore, the $WK^2$ of an electric transmission is a critical area. The generator $WK^2$ must be considered at the engine shaft and the motor $WK^2$ must be viewed at the drive sprocket through the output gear. The other parameter affecting acceleration is the load placed on the engine by the transmission at the time the engine is attempting to accelerate.

The XM-1 is a 58 Ton tank which is basically the M-60 with improved performance. The top design speed is 45 mph which could only be used comfortably on hard surfaces.

Continental is providing a 1500 hp diesel engine which drives through a mechanical-hydraulic transmission. It employs a hydraulic torque converter in conjunction with a four speed gear transmission. A certain speed range is covered by each gear ratio. In the lower portion of each speed range the converter is in operation. At, say, the midpoint of the range the converter is locked-up and the system operates as a mechanical drive.

With this type of drive, the power delivered to the drive sprocket peaks at four points. At other speeds the power is reduced either due to the losses in the converter or because the engine is overloaded or both. The peak power is about 85% of rated even at lock-up because of hydraulic spin losses in the transmission.

Considering that the SEGMAG system could achieve efficiencies between 90-95%, the steady state performance is clearly improved over the entire range of vehicle speed.

Several machines were considered for this drive, the pertinent data being presented in the following table:

|  | Generator | Motor (2 req'd.) |
|---|---|---|
| Rating, hp | 1500 | 750 |
| Speed, rpm | 3000 | 450/2880 |
| Dia., in. | 27 | 36 |
| Length, in. | 34 | 35 |
| Wt., lbs | 5000 | 4000 |

The size of the machinery evolved in these preliminary designs appears to fit into the available space in the XM-1 vehicle. The mechanical arrangement of components, however would have to be scrutinized more closely. The system weight of approximately 16,000 lbs appears to be a slight handicap and would have to be evaluated on the basis of the increased accelerating capabilities of the vehicle. The feasibility of this application can only be evaluated after an intensive analysis of the complete system performance over the required mission profiles and a detailed mechanical layout is completed. These tasks would be outside the scope of the present contract.

## 3.2.2 Amphibious Vehicles Propulsion Systems

During this period, several propulsion systems for amphibious vehicles were investigated. To gather information on the characteristics of these vehicles and their performance requirements, several visits were made. The first was to the U.S. Marine base at Quantico, Virginia to discuss the requirements of an advanced amphibious vehicle drive.

The present vintage of amphibious vehicles are 25 ton tracked vehicles with 8 knot water speed. They utilize engines with mechanical-hydraulic transmission for land operation and water jets at sea. For the advanced LVA under consideration, the most dramatic performance change desired is to raise the speed to the range of 35 to 70 knots. These high speeds indicate a departure from the displacement type vehicle. Candidate systems include planing hulls, surface effects, etc. In these cases, a drastic reduction in vehicle weight is required to bring the propulsion system within an acceptable power range.

Westinghouse presented a review of the various advanced machines under study and development with special emphasis on the SEGMAG machine concept and the ARPA program objectives.

Also performance characteristics for a typical tracked vehicle were presented and comparisons were drawn between mechanical and mechanical-hydraulic and electric torque converters. The electric drive provides ease of control, high maneuverability and high utilization of the prime-mover rating over a wide range of vehicle speeds. Also, electric drive offers superior acceleration capability.

The need to develop reversing current collectors for the drive motors was identified and a program to define specific machines and the control scheme was suggested.

The vehicle is in the very early stages of idea formulation. Therefore, the needs and the drive systems are too uncertain to permit an evaluation of the advantages that would be derived from an electric drive system.

Due to the limited funds, it appears that the USMC program will be restricted to vehicle concepts based on currently available components or development systems sponsored under a broader program.

Another visit made during this period was to the Naval Amphibious Warfare Board at Norfolk, Virginia. They were interested in the present state-of-the-art in electric propulsion systems as they might apply to re-power a range of amphibious vehicles that they operate

A short Presentation was given of Marine Propulsion Systems utilizing the ARPA developed SEGMAG machine concepts and other electric propulsion arrangements. Interest was indicated by the Navy for several potential applications.

Many questions were generated by these Operations Personnel regarding the application of the SEGMAG drive system. The majority of these questions concerned the liquid metal current collectors, and centered on the following particular categories: 1) The effect of pitch and roll on the liquid metal in the collectors. 2) The types and methods of seals used to maintain the liquid metal in the collectors. 3) The seals required to maintain the nitrogen gas in the machine and the amount of nitrogen required for inventory. 4) The amount of liquid metal discharged from the machine normally and under battle conditions. 5) The effect on safety to personnel in event of liquid metal leakage. 6) Due to the close tolerances in the current collectors, what provisions are incorporated into the machine for thrust absorbtion and thermal growth? 7) Due to the relative high mortility of these small vessels what are the economics of this drive system?

All of the questions were answered positively with experimentally-derived data and potential solutions proffered to the contemplated problems.

## SECTION 4

## CURRENT COLLECTION SYSTEMS

### 4.0 OBJECTIVES

The objectives of this task are to study liquid metal current collection technology and to identify the preferred systems for the segmented magnet homopolar machines.

During Phase I the specific objectives were: 1) to review the state-of-the-art of liquid metal current collection system technology; 2) to identify preferred liquid metals and preferred current collector designs under a variety of operating conditions; 3) to identify the operational problem areas which must be resolved for successful performance; 4) to establish the constraints which the liquid metal handling and purification systems must satisfy; and, 5) to establish an experimental program to resolve the problems associated with liquid metal current collectors.

During Phase II the objective was to evolve a liquid metal current collector suitable for unidirectional, constant speed machines of the SEGMAG type and to verify its effectiveness in the 3000 HP demonstration SEGMAG generator.

During Phase III the current collector technology will be extended to: 1) unidirectional high speed (96 m/s collector speed) generator appli-cations; and, 2) reversible and variable speed applications such as motors and torque converters.

### 4.1 PRIOR AND RELATED WORK

During Phase I of the present ARPA contract, a preferred current collector design was identified for unidirectional homopolar machines, such as the SEGMAG generator. This selection was based on a review study of the complex electromagnetic interactions and forces which will be experienced by functioning collector systems under a variety of operating conditions and liquid metals. The preferred collector design embodies an "unflooded machine gap", with the low density sodium-potassium liquid metal alloy (NaK) confined in narrow circumferential current transfer zones. The liquid metal alloy gallium-indium (GaIn) was selected as an alternative to NaK, especially for homopolar machine applications wherein relatively low speed and high ambient magnetic field operating conditions exist, or in certain situations where liquid metal handling may be considered a problem. The alternative choice of a higher density liquid metal was based on lower calculated power losses when run under the specified operating conditions. Although not as compatible as NaK with most structural and conducting materials, GaIn is quite easy to handle and lends itself to a relatively simple purification process.

Two of the greatest concerns in applying liquid metal current collectors are: a) the magnitude of power losses developed in the fluid; and, b) the confinement of fluid to the current collection zones during all machine operating conditions. A complete discussion of these concerns is contained in the previous reports under this contract.

During Phase II a liquid metal current collector test facility was constructed and an experimental test plan was implemented to resolve recognized problem areas in applying liquid metal current collectors. Part of this effort included an evaluation of collector width effects on the magnitude of the ordinary fluid dynamic power loss. The effect of ambient radial magnetic field and collector width variations on the eddy current power loss was also investigated. The remaining work effort consisted of experimentally evaluating the possible adverse effects which rotor rotational speed, radial magnetic induction, and load current have on liquid metal confinement in the collection zone. This effort culminated in the design and fabrication of the current collectors for the prototypic SEGMAG generator. A complete exposition of this work is contained in the previous reports under this contract.

## 4.2 CURRENT PROGRESS

During this report period, the 1.27 cm wide current collector was evaluated during the initial tests of the SEGMAG generator. These tests have verified the suitability of this current collector for use in homopolar machines of constant high speed (67 m/s collection).

Studies have now been initiated to: 1) extend the unidirectional collector technology to higher collector speeds (96 m/s) for generator applications; and, 2) develop reversible and variable speed collectors for torque converter and motor applications. This work has been divided into the following subtasks:

> 4.2.1 SEGMAG Collectors
>
> 4.2.2 High Speed Collectors
>
> 4.2.3 Flooded Collectors
>
> 4.2.4 Unflooded Collectors
>
> 4.2.5 Hybrid Collectors

## 4.2.1  SEGMAG Collectors

The demonstration SEGMAG generator was tested under high voltage-zero current (open-circuit test) and high current-minimum voltage (short-circuit test) conditions.  While running under these conditions the hydrodynamic and eddy current drag and ohmic power losses were determined for the generator collectors.  In addition, the operating characteristics of the liquid metal current collectors in regard to filling of the annulus and confinement or management of fluid spills within the generator were determined.  During most runs liquid metal (NaK-78) was continuously injected into each test collector at a nominal flow rate of 4.2 $cm^3/s$. Collector stator temperature was controllable but allowed to vary during some runs in an acceptable 75°-100°C range.

A few modifications to the current collectors are presently underway in order to increase the voltage and current output of SEGMAG, with retest scheduled for the next reporting period.

### 4.2.1.1  Power Losses

The collector ordinary viscous power loss was determined from results of a number of zero-field open circuit tests.  During these runs the six SEGMAG current collectors were filled either separately or in selected combinations.  The average ordinary fluid dynamic power loss when running at a nominal speed of 60 rps, based on twenty separate determinations, is 4.4 kW per collector.  This loss magnitude is essentially equal to the calculated value, but about 25% higher than that previously determined during "glove box" experiments with a similar design collector.  The average collector viscous drag power loss determined for speeds of 55, 47, and 30 rps are 4.0, 2.5, and 1.6 kW, respectively.

The collector eddy current drag power loss was determined from open circuit-field excitation tests made at the SEGMAG generator rated speed of 60 rps.   Power loss associated with the magnetic field was found to be relatively low, tending to increase first then fall off at the highest excitation levels.  The average  eddy current drag loss associated with the highest test level of magnetic induction (1000 amperes field current) is 0.6 kW per collector.  This loss determination is about 40% lower than that previously determined during "glove box" experiments with a similar design collector when subjected to an essentially radial magnetic field of 0.03 Tesla.  The highest eddy current drag loss (1.6 kW per collector) was found at a lower excitation level (800 amperes).  Signficant error in the eddy current losses reported for SEGMAG is possible since:  1) they are quite small in magnitude; and, 2) they were determined by subtracting two relatively large quantities of power, each determined from sequential but independent tests.

The collector ohmic power loss was determined from short circuit tests of SEGMAG, which were run at a nominal speed of 60 rps.  Surprisingly, the ohmic loss was found to be higher than either the viscous or the eddy current drag losses for current levels greater than 37,000 amperes. Future tests are planned to isolate the contact losses from other losses in the machine in order to determine more accurately their magnitude.

### 4.2.1.2 Collector Filling

A portion of the zero field-open circuit test period was devoted to evaluation of collector filling techniques. Perhaps the best filling procedure involved continuous injection of purified NaK into preheated collectors running first at low speed, then increasing to the desired operating or test speed. The collector stators were usually preheated to 75°C, a temperature considered from previous work to be above the critical level for good operation at 60 rps. Complete filling of each collector was evidenced by a reduction in the NaK inlet pressure, an increase in the NaK inlet flow rate, and an increase in the collector stator temperature. Similar techniques for filling and for detection of filling were established and employed during the previous work with experimental current collectors and, now, again confirmed here.

Potentially disturbing effects on the maintenance of a completely filled collector became evident during the open circuit-field excitation test and under conditions involving the highest load current during the short circuit test. Although the generated voltage showed no outward sign of instability during open circuit testing, the NaK inlet pressure steadily increased from its initial low level with increasing excitation current. In the second situation, a sudden rise in NaK inlet pressure and a corresponding reduction in NaK inlet flow rate were coexistent observations made when the load current reached 90,000 amperes. Both of the above incidents confirm the previously expressed concern for disruption of liquid metal in the annulus due to circulating and load current effects and point up the desirability of dynamically or continuously fed liquid metal current collectors, to prevent starvation of fluid in the annular gap.

### 4.2.1.3 Factors Affecting Containment

The collectors were capable of confining liquid metal to the current collection zones reasonably well under most operating conditions. When the collectors were completely filled with high purity NaK and running under steady-state high speed conditions the average loss of liquid metal per collector was generally in the range 0-0.047%, based on the inlet flow rate. Although spillage of NaK did occur it did not interfere with machine operation. Auxiliary drains were provided to accept such NaK loss from the collection zones when it occurred.

Generally a noticeable increase in the loss rate of NaK from the current collection zones was noted during the start-up speed transition periods, but, as under normal running conditions, this did not prevent machine operation. Significant leakage of NaK from the collection zones was also noted when SEGMAG was run at the highest excitation levels, when it was supplying the highest load current, and when the collector temperature was less than 65°C. As before, NaK spillage caused by these effects was also manageable.

## 4.2.2  High Speed Collectors

The objective of this task is to develop current collectors suitable for the high peripheral speeds that will be encountered in SEGMAG generators of 20,000 hp, 3600 rpm rating.  This implies collector speeds of 96 m/s as compared with 67 m/s for the 3000 hp SEGMAG demonstration generator.

Concerns for power loss and liquid metal confinement were previously evaluated theoretically and more recently experimentally in glove box and SEGMAG demonstration machine experiments.  Although the magnitudes of power losses and expulsion pressures are functions of machine operating conditions, liquid metal physical properties, and the collector geometrical shape, only the latter function lends itself to practical modification in regard to maximizing machine efficiency and minimizing liquid metal spillage from the collection zones.

In general, quite narrow collectors appear to be necessary even in the presence of low magnitude magnetic fields to achieve stable fluid flow conditions in the annulus.  This is necessary in order to minimize the larger expelling pressures in wide collectors caused by radial magnetic fields.

Possible confinement problems associated with narrow collectors attributed to ordinary fluid dynamic secondary flow effects, the accompanying potential for increased contact resistance, and resulting higher ohmic power loss are primary concerns to applications of liquid metal current collectors in very large powerful homopolar generators.

In preparation to evaluate candidate collector designs for a 30,000 hp, 3600 rpm SEGMAG generator, the current collector test stand is being modified for higher speed capability, controlled circulation of load current through the test collectors, and acceptance of narrower width collectors.

### 4.2.2.1  Objectives of Experimental Tests

Although the 1.27 cm wide simple rectangular shaped cross-section current collector performed satisfactorily to permit a feasibility demonstration of the SEGMAG machine concept, an improved collector is required for similar but higher speed and higher power generators. The following objectives (technical approaches) are reflected in the experimental test plan designed to develop an improved current collector for the 30,000 hp, 3600 rpm SEGMAG generator.

- Reduce collector power losses; viscous, eddy, ohmic (collector width reduction, insulated flat side walls, silver plated contact surfaces).

- Circumvent the need for critical high temperature to assure collector filling (cover gas of lower density, modify collector geometry).

- Improve sealing against liquid metal spillage (collector geometry, seal design concept).

- Resolve concerns regarding solid-liquid-solid contact electrical resistance (direct measurement, high load current, high rotor speed).

- Determine consequence of high speed operation on collector power losses, collector filling, and confinement of liquid (direct evaluation at high speed).

- Demonstrate an ability to simultaneously supply multiple current collectors with liquid metal from a common source.

### 4.2.2.2  Specific Contact Potential Experiments

Measurement of various performance parameters during the SEGMAG evaluation tests, and subsequent calculations to demonstrate SEGMAG current collector viability, showed that a measured value of NaK to collector contact resistance was necessary. The calculation of ohmic power losses in the generator due to load current crossing the collector gap could then be based upon experimentally measured contact resistance values. An experimental arrangement was constructed wherein NaK at varying temperatures (room temperature to 150°C) could be circulated at varying flowrates through an insulated cell containing two copper electrodes. The surfaces of the electrodes were given various surface pretreatments. The following section reviews the need for this work and the results of the experiments.

Ohmic power loss due to load current crossing the collector gap is determined in a straightforward manner by the equation:

$$P_o = \frac{I^2}{2\pi rw} \left(\frac{d}{\sigma} + \epsilon_k\right) \tag{4.2.2.1}$$

where:  $P_o$ = ohmic power loss per collector, watts.

$I$ = collector load current, A.

$r$ = collector rotor radius, m.

$w$ = collector electrical contact width, m.

$d$ = collector radial gap dimension, m.

$\sigma$ = electrical conductivity of liquid metal, mhos/m.

$\epsilon_k$ = specific contact potential (solid-liquid-solid contact pair), Vm$^2$/A.

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It is implied in the above expression that the liquid metal is continuous and completely fills the collector annular gap during machine operation and that the specific contact potential, $\epsilon_k$, is known for the solid-liquid-solid contact material combination. If the liquid metal is not continuous in the collector gap and/or if the contact resistance is inadvertently high (i.e., poor wetting, gas film, etc.), the ohmic power loss may be increased significantly.

A comparison of the magnitudes of the two terms in the above ohmic power loss expression is of interest to contrast their relative importance. The specific contact potential depends on the solid and fluid metals which comprise the collector. Reported $\epsilon_k$ values for the copper-NaK-copper contact combination fall in the range 3 to $5 \times 10^{-9}$ $Vm^2/A$.[1,2] Typical radial gap dimension (d) and liquid metal (NaK-78) conductivity ($\sigma$) values are $1.59 \times 10^{-3}m$ and $2.2 \times 10^6$ mhos/m, respectively. The corresponding ratio of $\epsilon_k$ to $d/\sigma$ is 5.5. Assuming that the reported values of specific contact potential are valid, contact resistance between the liquid and solid members of the collector causes a 6.5X increase in the ohmic power loss. Consequently, contact resistance must be given careful consideration when applying collectors in machines which impose very large load currents. Since the ohmic power loss is a squared function of the load current, rather large losses may be encountered in situations wherein high contact resistance exists.

Specific contact potentials of $2 \times 10^{-9}$ and $0.1 \times 10^{-9}$ $Vm^2/A$ were determined from the recent experiments made at Westinghouse wherein NaK-78 was flowed at relatively low velocities (10 m/s) through a simple rectangular shaped quartz cell with plain and silver-gold plated copper electrodes, respectively. The ratio of $\epsilon_k$ to $d/\sigma$ for the latter case is 0.14, and the corresponding increase in ohmic power loss due to contact resistance is only 1.14X.

To resolve concerns posed by contact resistance, experiments are planned to obtain direct measurements of specific contact potential for test collectors as a function of typical machine operating conditons. The test collectors will be 14-inches in diameter and operate at 3600 rpm with currents to 30,000 amperes.

## 4.2.3  Flooded Collectors

During this reporting period, a preliminary investigation was made of
flooded current collectors for an 8000 HP disk-type homopolar machine
(DISKMAG).  The greatest areas of concern are associated with power loss
along the flat sides of the disks due to MHD effects, and excessive fluid
pressure in the NaK with resulting thrust forces on the rotor and its
bearings.  The studies are continuing.

### 4.2.3.1  Detailed Progress

One possible solution to the problem of containing conducting fluid in
the annular current collector gaps of a horizontally-mounted machine is
to completely fill the machine with liquid metal.  Then, regardless of
low speed running or bidirectional rotation requirements, there is no
concern for the loss of liquid metal from the collector sites.  All
internal component parts of the machine must, of course, be carefully
insulated to minimize the effect of electrical short circuit paths
between current collectors of different potential.

A major concern to using the "flooded gap" concept in large homopolar
machines is that of ohmic, hydrodynamic, and electrodynamic power losses
created in the fluid during machine operation.  Such losses are due to
short circuit currents and fluid drag forces, the latter resulting from
velocity gradients in the liquid because of inertial and electromagnetic
effects and the large fluid-solid contact areas.

Rhodenizer has treated the "flooded gap" collector case for low speed
disk-type homopolar motors which utilize high magnetic induction from
superconducting excitation coils.[3]  He assumes that laminar fluid flow
exists along the flat side walls of adjacent rotating and stationary
disk pairs.  This assumption is based on an unconfirmed requirement that
the inertial body force (Reynolds number) be no greater than 1000 times
the electromagnetic force (Hartman number).  Additionally, by selectively
insulating certain disk side walls, induced electrical current flow
through the fluid interacts with the applied axial magnetic field in
such a way that the resulting velocity and current distributions tend to
minimize the short-circuit effects   (see Fig. 4.2.3.1).  Under these
conditions, the main (bulk) fluid flow velocity is equal to that of the
rotating disk on one side (uninsulated) and zero on the opposite side
(insulated).  Thus, the fluid acts as extensions of the rotating disks
on one side and as extensions of the stationry facing disks on the other.
The result is that only a thin sheet of liquid metal near the fluid-solid
boundary acts as a short-circuit path across each voltage generating disk.
In this manner losses due to short circuiting of the disks is reduced
but with some loss due to the above mentioned MHD interactions.

The following expressions useful for estimating power loss in the radial
gap, $P_{rg}$, and the axial gap, $P_{ag}$, were developed by Rhodenizer and

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Stationary Disc
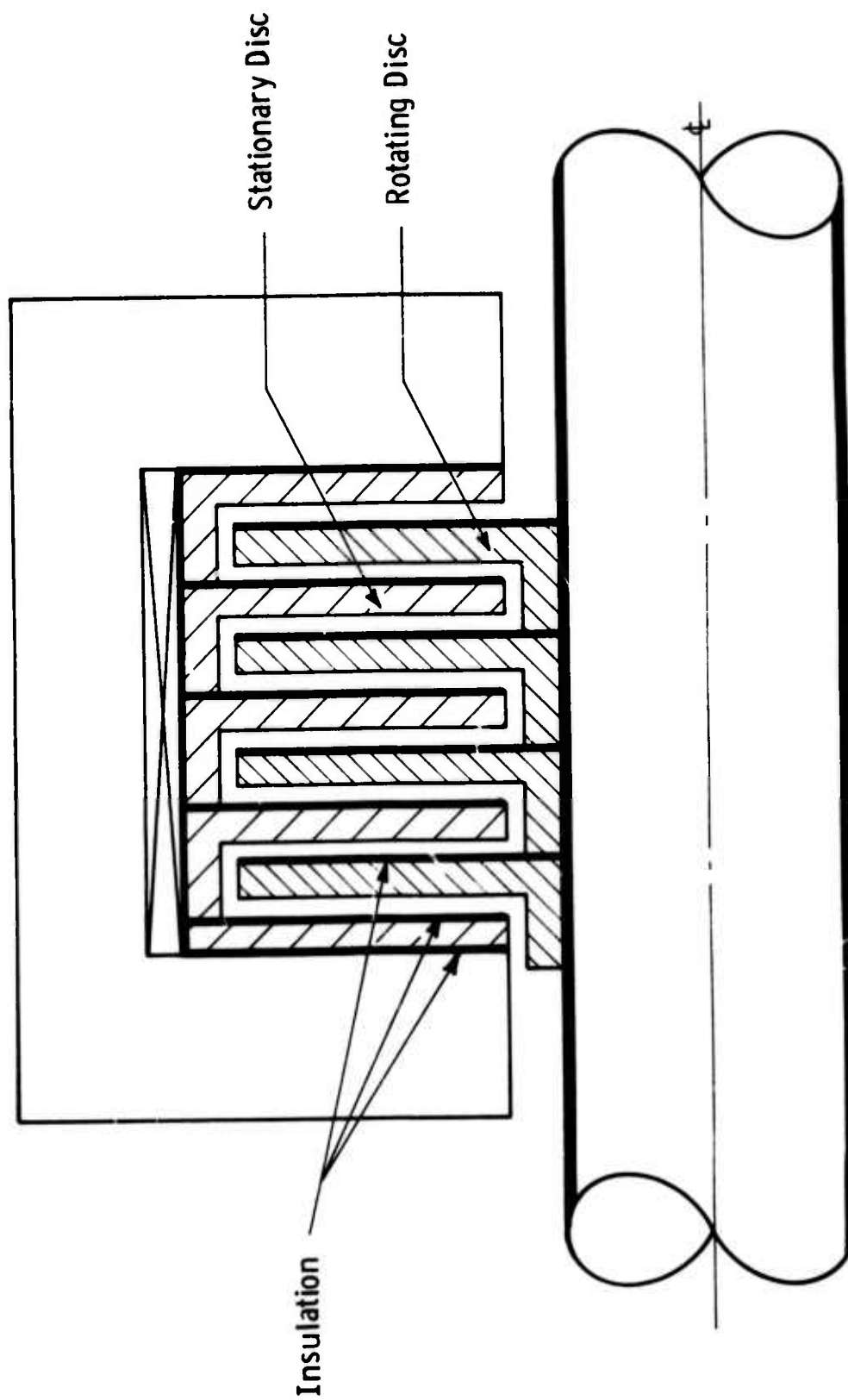
Rotating Disc

Insulation

Fig. 4.2.3.1: Concept of electrically insulating machine disks

presented here for reference. Turbulent flow regime is implied for fluid in the radial gap and, as previously discussed, laminar flow along the axial gap flat side walls. Symbols used in the expressions correspond with those presented in a previous section (Table 2.3.1). General symbols in the expressions, when used, represent the corresponding parametric terms associated with the specific collector in question.

$$\delta = \frac{2JBd}{f\rho v^2},$$ (4.2.3.1)

where $\delta$ = the collector constant, and it is the ratio of a Lorentz circumferential body pressure acting on the fluid to the inertia pressure.

$J$ = collector current density = $\frac{I}{2\pi Rw}$, $A/m^2$

$v$ = collector peripheral velocity = $\omega R$, $m/s$.

If $\delta > 1$,

$$P'_{rg} = \left\{ \frac{f\rho v^3}{8} \left[ 2(1+\delta) \sqrt{2\delta-1} \right] 2\pi Rw \right\},$$ (4.2.3.2)

where $P'_{rg}$ = radial gap MHD power loss per collector, watts.

If $\delta < 1$,

$$\left\{ \frac{f\rho v^3}{8} \left[ 1+3(\delta)^3 \right] 2\pi Rw \right\},$$ (4.2.3.3)

$$P_{rg} = \sum P'_{rg} = N (P'_{rgi} + P'_{rgo}),$$ (4.2.3.4)

where $P_{rg}$ = total machine radial gap MHD power loss, watts.

$P'_{rgi}$ = radial gap MHD power loss per inner collector, watts.

$P'_{rgo}$ = radial gap MHD power loss per outer collector, watts.

$$P_{ag} = \pi B_x (n\sigma)^{\frac{1}{2}} \omega^2 N R_o^4 \left[ 1 - \left( \frac{R_i}{R_o} \right)^4 \right],$$ (4.2.3.5)

where $P_{ag}$ = total machine axial gap MHD power loss, watts.

$$P_o = NI \left\{ \frac{1}{\sigma} (J_o d_o + J_i d_i) + \epsilon_k (J_o + J_i) \right\}, \qquad (4.2.3.6)$$

where $P_o$ = total ohmic power loss in radial gap, watts.

Using the above expressions and data from Table 2.3.1, the following calculated values of power loss for the 8000 hp disk-type motor are shown below. Estimates of other machine losses are also presented.

TABLE 4.2.3.1

Power Losses for a Typical 8000 HP Disk-Type Motor (DISKMAG)

| Power Loss Mode | Power Loss, kW |
|---|---|
| Radial Gap ($P_{rg}$) | 18.26 |
| Axial Gap ($P_{ag}$) | 119.06 |
| Ohmic ($P_o$) | 31.01 |
| Machine (conductor + excitation) | 115.49 |
| Total | 283.82 |
| % of Machine Rating | 4.76 |

### 4.2.4  Unflooded Collectors

In a horizontally mounted machine with an unflooded active length, the collector design problem becomes one of confinement of the liquid to the annular collector gap.  For a motor, the confinement technique must be independent of rotor speed and direction of rotation.  Use of centrifugal forces induced by disk rotation, as in the case of high speed generators, cannot be used as the sole device for achieving containment of the liquid metal.  The objective of this study is to develop new concepts for the current collectors in an "unflooded" motor application, to evaluate these, and to select the most promising ones for more detailed invetigation.

During this reporting period, design objectives were established for the unflooded reversing collector, and potentially useful techniques were defined, and outlined for use in the definition of new collector configurations.  Evaluation criteria have also been established to provide uniform screening of the generated concepts.

#### 4.2.4.1  Reference Unflooded Motor Design-Collector Requirements

A "reference" motor design was defined to establish approximate parameters as requirement guides (or boundary conditions) for the current collector design.  Table 4.2.4.1 lists the corresponding collector requirements.

#### 4.2.4.2  Collector Concepts and Selection Criteria

A list of categories or classifications of reversing collector concepts was established as one tool for the generation of new ideas.  This list (Table 4.2.4.2) defines potentially useful techniques or physical properties which may be used to develop specific collector configurations.

The first major category (A) considers an annular liquid metal conductor ring which is confined by the various listed sealing techniques.

The "Conducting Seal" (B) intermixes or combines the sealing and conduction functions within one more-or-less homogeneous structure.

The "Low-Speed Flooding" or "Low-Speed Brush" concept (C) would utilize centrifugal effects for containment of the liquid metal at higher speeds but would also use centrifugally actuated brushes which engage at speeds below "drop-out" rpm, or instead would permit flooded-gap operation at the lower speeds when gap power losses would be smaller.

"Axial Injection (or Radial Ejection)" (D) would use the inertial forces of recirculating liquid metal to contain or entrain the collector liquid.

## TABLE 4.2.4.1

## Unflooded Motor Reference Design-Collector Requirements

1. Power Rating - 40,000 hp

2. Maximum Speed - 180 rpm (18.9 rad/sec)

3. Collector Diameters:  outer - 72 in. (1.83 m), for drum (SEGMAG and disk-type machines (DISKMAG)

   inner - 32 in. (0.81 m), for disk-type machines

4. Axial and Radial Dimensions Allocated for Current Collector Cross-section - 1.5 in. ($3.81 \times 10^{-2}$m)

5. Maximum Permissible Current Density - 16,000 amps/in². ($2.48 \times 10^7$ A/m²)

6. Maximum Collector Current - 300,000 amps

7. Axial Field through Collector - 15,000 gauss (1.5 Tesla)

8. Maximum Radial Field through Collector - 500 gauss (0.05 Tesla)

9. Liquid Metal Leakage from Collector - near zero

10. Maximum Power Loss per Collector Pair - 65 hp ($4.85 \times 10^4$ w)

The above values were used to establish the following related parameters:

11. Tip Speeds (from 2 and 3):  outer - 57 ft/sec (17.2 meter/sec)

    inner - 25 ft/sec (7.7 meters/sec), for disk-type machine

12. Bearing Radial Clearance - 0.012 in. ($3.05 \times 10^{-4}$m) (based on 1 mil/in. (1 mm/m) diametral clearance and a 24 in. (0.61 m) shaft dia., necessary for 3 per unit torque at 15,000 psi ($1.03 \times 10^8$ N/m²) shear design strength)

13. Minimum Width of Liquid Metal Contact:  outer - 0.083 in. ($2.11 \times 10^{-3}$m) (from 3, 5 and 6)

    inner - 0.187 in. ($4.74 \times 10^{-3}$m), for disk-type machine

ADDITIONAL REQUIREMENTS

1. Collector must pass 150% rated current at zero speed for 10 secs.

2. Collector must be operable cold without pre-heating.

3. Collectors for a machine must be supplied from a common liquid metal source.

4. Collector must be capable of deceleration from full speed forward to full speed reverse in several seconds.

5. Collector shall be designed for sudden stops.

6. Collector shall be designed for sudden load changes.

7. Collector shall be designed to provide for axisymmetric current flow.

The following assumptions will be made, but will be re-evaluated, if necessary, when more specific machine and collector designs are available:

1. Relative axial movement between the rotor and stator, will be neglected, and a perfectly centered collector will be assumed.

2. Coolant channels or other cooling techniques will not interfere with the current collection design.

3. Joining of any required conductor bars to collector rings will not interfere with collector design.

4. Any mechanical strengthening rings will be outside of the current collector envelope (i.e., the collector will not have to support the loading of other components, due to centrifugal force or relative thermal growth).

5. Changes in radial gap, due to operation, will be assumed to be negligible.

6. Insulation requirements will not interfere with collector design.

## Table 4.2.4.2

### Classification of Unflooded Reversing Collector Concepts

A. Sealed Annular Chamber (Seal Types)

1. Rubbing - lip seal, face, radial
2. hydrostatic - face, radial, floating
3. hydrodynamic - face, radial, floating
4. labyrinth - clearance, knife/groove, slinger, transverse gas flow, adjustable
5. buffer fluid - liquid, gas, grease, wax
6. electromagnetic retention - special field/current source
7. absorbent (wick) - labyrinth, slinger/wick
8. low-speed only - centrifugal, electromagnetic
9. magnetic fluid
10. surface tension - wetted/non-wetted surfaces
11. solidification - thermal, chemical

B. Conducting Seal

1. conducting wick - stationary/rotating, fiber, foam
2. hydrodynamic/hydrostatic
3. flooded (alternately) labyrinth

C. Low-Speed Flooding or Low-Speed Brush Contacts

1. pressure-controlled volume
2. pump/control system
3. gas injection

D. Axial Injection (or Radial Ejection)

1. inertial containment
2. venturi effect

E. Zero Pressure (free-fall)

F. Constant-Speed Seal-Rotor

## TABLE 4.2.4.3
## Evaluation Criteria for Current Collectors

1. Containment (Leakage)
   a) aerosol
   b) liquid

   [free-surface stability, gravity force, acceleration/deceleration (angular/transverse), momentum changes (coriolis)]

2. Power Loss
   a) viscous
   b) ohmic (bulk & contact)
   c) MHD
   d) friction (rubbing)

3. Circulation System Requirements
   a) pressure/flow control
   b) purification/separation

4. Radial/Axial Clearance
   a) bearing clearances
   b) dimensional tolerance
   c) thermal growth
   d) centrifugal growth

5. Mechanical Adequacy
   a) thermal stress
   b) rotational (torque) loading
   c) hydraulic load (static/dynamic)
   d) centrifugal loading/stresses
   e) MHD forces (radial, tangential, axial)
   f) wear (rubbing, erosion)
   g) vibration/oscillation stability
   h) load rate (shock)

6. Temperatures (cooling)
   a) heat generation (see power loss)
   b) temperature distribution (collector and rotor conductors)

7. Electrical Adequacy
   a) voltage drops
   b) recirculating currents
   c) asymmetry effects (including variable NaK thickness/area)

8. Material Compatibility
   a) chemical
   b) mechanical (e.g., rubbing surfaces)

9. Assembly

10. Fabricability

11. Maintenance

In the "Zero Pressure" system (E) the liquid metal in the collector zone is caused to flow in a manner that would minimize the pressure drop across the seals, thus minimizing leakage flow. As an example, the liquid metal might be introduced at the top of the collector and the annulus cross-sectional area varied to accept a variable velocity caused by gravitational acceleration.

A "Constant-Speed Seal-Rotor" (F) would be an added ring which would be driven at a fixed speed, independently of the machine rotor speed, and which imparts sufficient rotational velocity to the liquid metal to retain it in the collector region through centrifugal action.

The collector configurations developed from this list and through other techniques will be subjected first to a qualitative screening and then more detailed analysis for the more promising concepts. The many criteria listed in Table 4.2.4.3 will be considered in the screening process, although initial evaluation will be based upon the primary concerns of confinement and power loss.

### 4.2.4.3  Containment System Pressure

The primary forces which act to expel the liquid metal from the collector region, include those due to machine load current, radial field, and gravity.

During Phase I of this effort, the force caused by changing field excitation was found to be small (see Table 4-2, page 4-11 of Semi-Annual Technical Report for Period Ending May 31, 1973) and therefore will be neglected at this time. Although additional acceleration or "g"-loading forces are expected to be significant, these are dependent upon the specific application. They are expected, at worst, to cause only short-term perturbation of the current collector conditions, but the "g"-load effect will be considered further in detailed analysis of the selected collector concepts.

The required containment pressure to oppose the machine load current force is (Sec. 4.2.4, Semi-Annual Tech. Report, Period Ending May 31, 1974):

$$P_L = (2n-1) \; 6.28 \times 10^{-7} \; I_p^2 \qquad\qquad (4.2.4.1)$$

where:  $P_L$ = axial pressure in the liquid metal, $N/m^2$.

  $n$ = number of series load circuits ($n = 1$ assumed for present study).

  $I_p$ = load current per unit length of collector periphery, A/m.

For the reference design (outer collector):

$$P_L = 6.28 \times 10^{-7} \ (300,000/1.83\pi)^2 = 1710 \ N/m^2 \ (0.25 \ psi)$$

The similar term relating to radial field effect will be:

$$P_{w/2} = 9.82 \times 10^{-9} \ (\frac{\sigma \omega r B_y}{d})^2 \ w^4 \qquad\qquad (4.2.4.2)$$

where: $P_{w/2}$ = maximum eddy current-induced pressure in the liquid, $N/m^2$.

$\sigma$ = electrical conductivity of liquid metal, mhos/m.

$\omega$ = rotor angular velocity, rad/sec.

$r$ = collector rotor radius, m.

$B_y$ = radial magnetic field, Tesla.

$d$ = collector radial gap dimension, m.

$w$ = collector electrical contact width, m.

If the fixed parameters for the reference design (outer collector) are used, with NaK as the liquid metal ($\sigma = 2.20 \times 10^6$ mhos/m):

$$P_{w/2} = 9.82 \times 10^{-9} \ (2.2 \times 10^6 \times 18.9 \times 0.915 \times 0.05)^2 \ w^4/d^2$$

$$P_{w/2} = 35,500 \ w^4/d^2.$$

This relationship is plotted in Fig. 4.2.4.1.

To establish the order of magnitude of this pressure, an effective collector width of $2.54 \times 10^{-2}$ m (1 in.) and a radial gap of $1.59 \times 10^{-3}$m (0.0625 in.) were used to calculate the expelling pressure:

$$P_{w/2} = 5850 \ N/m^2 \ (0.85 \ psi)$$

The pressure at the bottom of the collector annulus, due to the gravity force will be:

$$P_g = 2r\gamma,$$

where: $P_g$ = is the pressure increase from top to bottom of the collector annulus, due to gravity, $N/m^2$

r = collector radius, m

$\gamma$ = weight density of the liquid metal, $N/m^3$.

For NaK, with a weight density of 8,310 $N/m^3$, the gravity pressure rise for the outer collector will be:

$$P_g = 1.83 \times 8,310 = 15,210 \ N/m^2 \ (2.21 \ psi).$$

The combined effect of these three factors would produce a maximum fluid pressure of 22,770 $N/m^2$ (3.3 psi), with the gravitational force as the major contributor (2/3), and the containment system must be adequate for a slightly higher pressure to permit some filling or contact pressure at the top of the collector.

A similar analysis as the above but for the inner collector of a disk-type machine would yield a lower total pressure of 16,610 $N/m^2$ (2.4 psi).
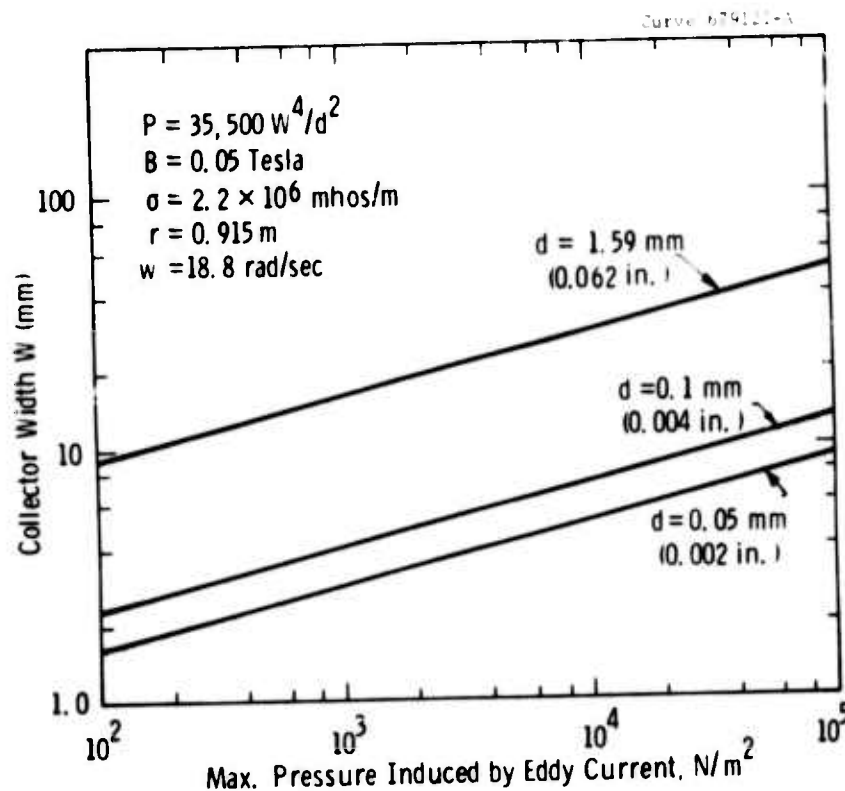


Fig. 4.2.4.1: Eddy current induced pressure in unflooded collector

### 4.2.5 Hybrid Collector

The hybrid current collector consists of a series of "floating pads" which contain liquid metal and utilize inherently small clearance with the rotor to minimize liquid metal leakage. The hybrid collector concept combines into one design the advantages of liquid metal and solid brush collectors.

A detailed study of the hybrid collector concept will begin in January 1975. The study will include considerations of power losses, requirements of necessary or supporting liquid and gas flow systems, development of an optimum or preferred geometrical configuration, and problem area definition.

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## SECTION 5

## LIQUID METAL SUPPORT SYSTEMS

### 5.0 OBJECTIVES

The objectives of this Task are: 1) to investigate the compatibility of candidate machine materials with NaK and GaIn as well as with potential decontamination solutions; 2) to perform literature, analytical, and experimental studies to identify suitable materials and suggest alternate choices where necessary; 3) to design, fabricate, and test the liquid metal loop and cover gas systems that will be required in the SEGMAG generator; and 4) to establish the operating parameters and interactive responses of these systems.

During Phase I, the objectives were to identify the materials requirements and related problems for the segmented magnet homopolar machine, with particular emphasis to the long term compatibility problems between the selected liquid metal and the electrical conductors, insulation and structural materials in the system.

In Phase II, the objectives were: 1) to identify experimentally the SEGMAG machine materials that are compatible with NaK; 2) to provide a test facility to evaluate candidate current collectors under simulated machine environment; 3) to provide liquid metal and cover gas systems for the SEGMAG demonstration machine; and, 4) to provide test facilities for the SEGMAG and GEC machines.

During Phase III, the auxiliary equipment developed under Phase II will be further utilized in the SEGMAG test program. The SEGMAG liquid metal system will be further developed and simplified. Support systems will be developed for use in torque converter and motor applications where reversible and variable speeds are encountered. GaIn technology studies will be pursued with respect to machine requirements.

### 5.1 PRIOR AND RELATED WORK

The work performed under this task is summarized below and is more fully described in our previous reports under this contract.

NaK was selected as the reference liquid metal, with GaIn as the alternate choice.

An extensive materials compatibility program (Table 5.1) was conducted, and the selection of materials for use in SEGMAG was based on their ability to withstand NaK exposure in a simulated machine environment.

Investigation was made of the chemical problems associated with wetting between NaK and copper or copper-based alloys.

Procedures were established for the disassembly and decontamination of machines using NaK and GaIn. Liquid metal recirculation and purification loops (Figs. 5.1 and 5.2) were designed, fabricated, tested, and employed in SEGMAG performance tests to maintain NaK in the current collectors. Cover gas recirculation, purification, and pressure maintenance systems (Fig. 5.3 and Fig. 5.4) were designed and constructed for SEGMAG performance tests. Full scale prototype current collectors (Figs. 5.5 and 5.6) were developed, tested and characterized prior to their employment in SEGMAG. The SEGMAG test bed, instrumentation, coolant system, and performance readout networks were developed and constructed for the machine evaluation tests.

## Table 5.1 - Candidate SEGMAG Materials Evaluated for NaK Compatibility

ORGANIC MATERIALS:

Insulations:
1. Kapton, type H, polyimide film, 2 and 3 mil thickness
2. Rotor Bar Insulation

Coatings:
1. Coating-phenolic-alkyd paint
2. Electrostatically deposited epoxy coatings type 725, 727 and 4-TK725

Silastic Sealants:
1. 116 RTV
2. 732 RTV

Banding Tapes:
1. polyester on glass
2. acrylic modified epoxy on glass
3. polyester on experimental fibers

Laminates:
1. Glass cloth base, silicone resin
2. Glass cloth base, epoxy basin

Miscellaneous:
1. Banding Pads
2. Cooling Fluid Wemco C
3. Eastman 910 (MHT) adhesive
4. Potting compound 53841-MU silica filled epoxy

INORGANIC MATERIALS:

Seal Materials:
1. 90 WGI, 5 Ag, 5CaF$_2$ (WGI-A)
2. 80 WSe$_2$, 20GI (WGI)
3. C/Graphite $\bar{w}$ MoS$_2$ (SK235 and SK278)
4. EVC Graphite
5. 80 WSe$_2$, 20GI with oxide coat (WGI-O)
6. C/Graphite with resin binder (SK-218)
7. Pure WSe$_2$
8. CR-218
9. CR-219
10. MF343 (Bronze 1 Graphite)
11. 1257 C/Graphite
12. Boron Nitride + 3 w/o Boric Oxide (BN-O)
13. Impervious Pyroimpregnated Graphite (LEM-2)
14. Raython Pyrographite (LEM-1)
15. High Density Graphite
16. AXZ Poco Graphite (d - 1.5 g/cc)
17. AXM Poco Graphite (d - 1.8 g/cc)
18. AXF Poco Graphite (d - 1.9 g/cc)
19. ATJ Graphite

Braze Alloys:
1. soft solder (copper and copper & nickel plated)
2. silver solder
3. nicrobraze

Structural Metals:
1. rotor forging
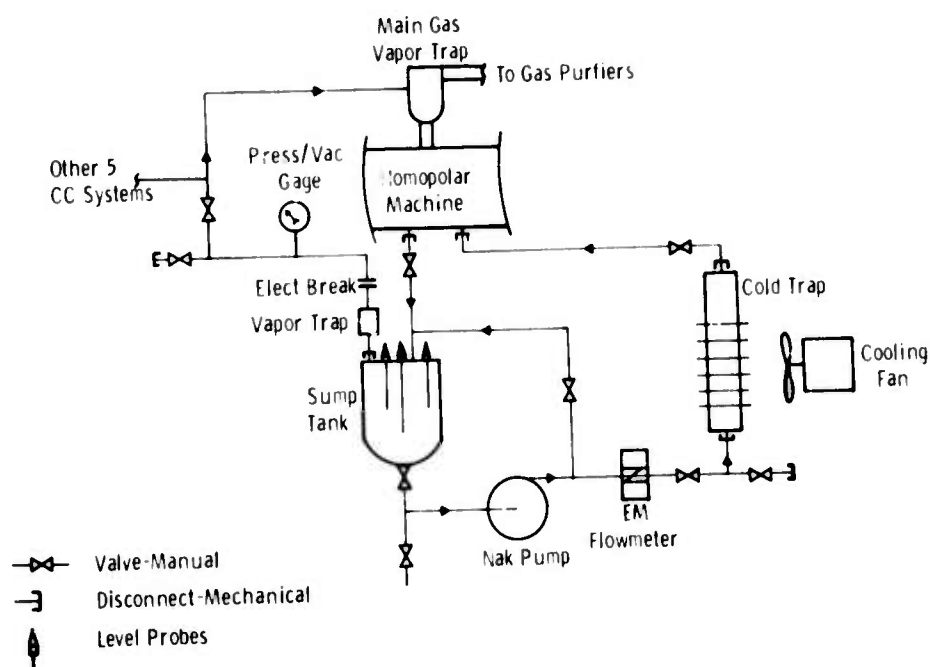2. copper current collector
3. housing

Dwg. 5207A75



Fig. 5.1: Small NaK loop concept for servicing each current collector independently
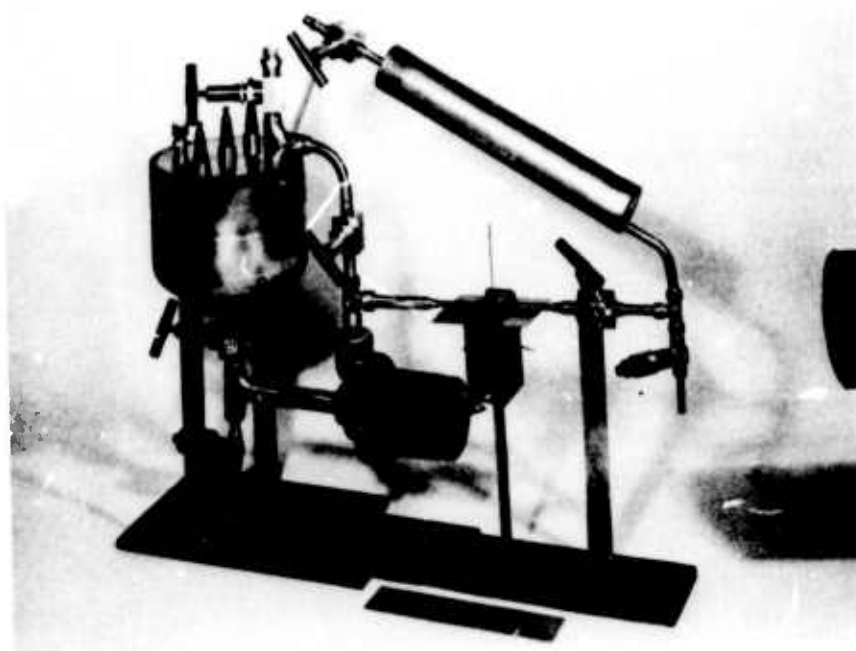


Fig. 5.2: Assembled NaK loop for current collector service in prototype SEGMAG machine

Fig. 5.3: SEGMAG cover gas systems



Fig. 5.4: Internal components of central gas purifier station for the SEGMAG homopolar machine

5-4
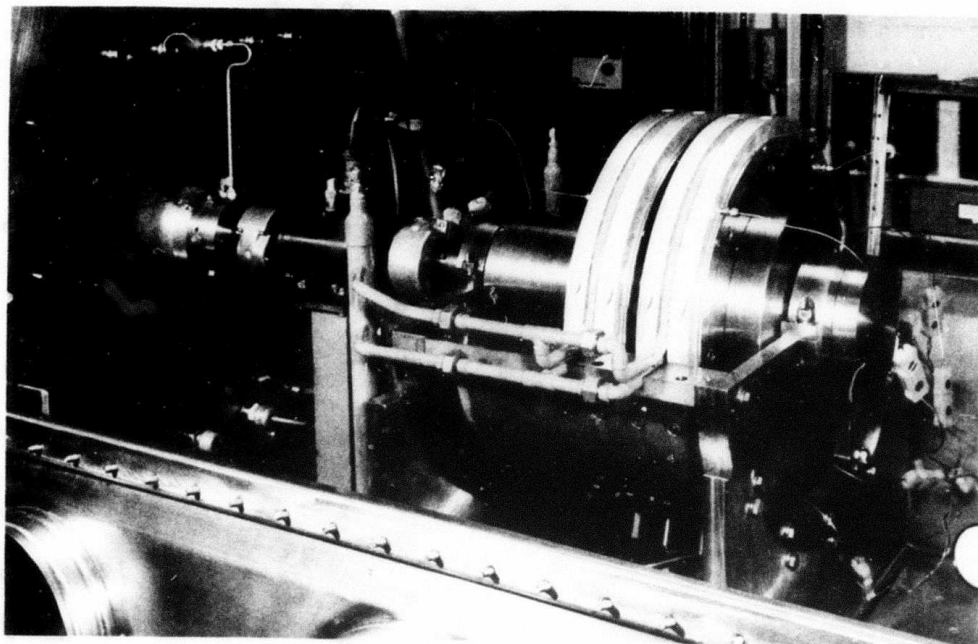
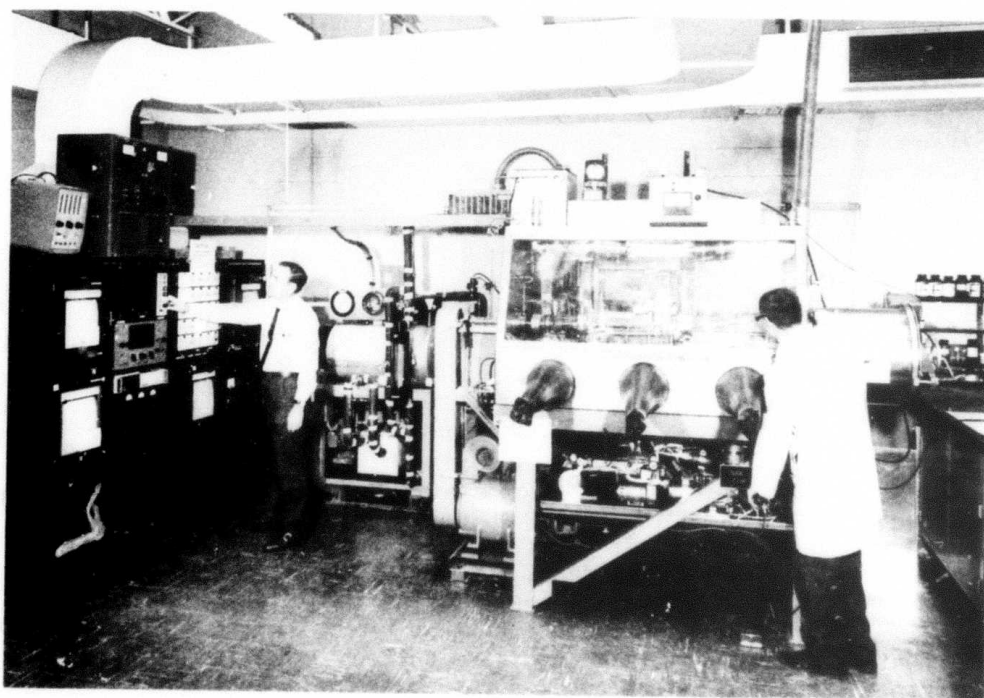Fig. 5.5:  Two Current Collectors in glove box for evaluation with NaK



Fig. 5.6:  Liquid metal current collector test stand

## 5.2 CURRENT PROGRESS

### 5.2.1 SEGMAG Performance Tests

The NaK loop purification and supply system performed well throughout the SEGMAG test program. All six NaK loops operated in accordance with design criteria. Flow control from 10-20 cc/min to 800 cc/min was good and flow rates remained stable after steady state operating conditions had been achieved. Minor plugging problems were noted (i.e., a decrease in flow) during initial loop startup and during transient conditions. The plugging during initial loop/SEGMAG operation resulted from overcooling the cold trap (heat exchanger - filter) and at other times (machine transient modes) when the NaK system temperature was increased rapidly in the machine. In all cases, the plugging occurred at the cold trap discharge line (i.e., just prior to machine entry), and was corrected by applying a heating tape to that area.

A prototype NaK loop, of the same geometry and construction as those employed in the SEGMAG test facility, has exceeded 9000 hours life test while continuously circulating NaK at 200 cc/min.

Work was initiated in a new area, that of supplying many current collectors with recirculating NaK from a common supply. As part of this investigation, several methods for breaking electrical continuity in a flowing NaK stream are being evaluated. Without a flow breaking technique, the electrically conducting NaK stream would short out collectors at different potentials, and contribute to high $I^2R$ losses in the machine. The flow breaking techniques under consideration include: mechanical, hydraulic, pneumatic, fluidic, and hybrid techniques. Flow into and out of the collectors must be considered separately as the flow pattern and pressures are different in each case. Criteria being employed to evaluate these techniques include reliability, cost, complexity, and size of the system as well as flow rate of NaK.

SEGMAG cover gas systems, as previously described,[1] performed well during the SEGMAG evaluation tests. Heated machine (80°C) vacuum degassing cycles prior to cover gas ($N_2$) backfilling and recirculation through purification towers were effective in removing $O_2$ and $H_2O$ (V) contaminants. Machine cover gas impurity levels were typically 1 ppm $O_2$ and 1 ppm moisture during most of the SEGMAG test conditions. The highest impurity level recorded was 3 ppm $O_2$ during the high power (high current) phase of the test program. Cover gas auxiliary systems, i.e., NaK drain lines, gas shaft seal, and auxiliary NaK blowdown lines, functioned well during the tests. A series of intercollector NaK blowdown lines performed quite well during SEGMAG tests. These lines provided for continuous, or intermittant removal of spillage NaK (from current collectors) which accumulated between collectors inside the machine. Emptying into graduated reservoirs, the system showed the rate of NaK loss during transient and stable conditions (reported in Section 2.1.2).

### 5.2.2 Gallium-Indium Technology

Although NaK$_{78}$ is the preferred current collection fluid for constant, high speed machines (generators), eutectic Gallium-Indium, 14.2-16.5 at .% Indium,[2,3] may be the more suitable fluid for slow, variable speed machines (motors). The primary reasons being: (1) eutectic Gallium-Indium is inherently easy to handle, because it does not react violently with water vapor or oxygen as does NaK$_{78}$ (however, care must be exercised because of its toxicity[4]); (2) it has a higher density[5] than NaK$_{78}$, it is therefore less influenced by MHD forces; (3) it is easily purified by simple electrolysis[6]; and, (4) it has a higher electrical conductivity than NaK$_{78}$.[7] Thus, since viscous losses are less important in low speed machines than in high speed machines, eutectic Gallium-Indium may be the more desirable current collection fluid.

In an effort to aid the electro-mechanical engineers in designing homopolar machines that will employ eutectic Gallium-Indium as a current collection fluid, a machine designer's guide to Gallium-Indium technology is being prepared. This guide is intended to cover the following aspects of Gallium-Indium technology: (1) physical and chemical properties; (2) compatibility with organic, inorganic, and structural metals; (3) machine degass and start-up procedures; (4) decontamination and clean-up schemes; (5) current collector wetting; (6) purification techniques; and (7) safety and toxicity.

### 5.2.3 Advanced Collector Designs

Work was initiated to extend the liquid metal support systems technology to other advanced collector designs of the following types: flooded, unflooded reversing, and hybrid. Each of these current collectors require varying support system capabilities.

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7. Zrnic, D., and D. S. Swatik, "On the Resistivity and Surface Tension of the Eutectic Alloy of Gallium and Indium," J. of the Less - Common Metals, 18, 67-68 (1969).

## SECTION 6

### SEAL STUDY

## 6.0 OBJECTIVES

A study of the sealing problems between the liquid metal, bearing oil system, and the environment shall be conducted. Seal system designs will be evolved for both the SEGMAG and SMHTC machines.

There are two subtasks to the seal study:

1) Confinement of liquid metal to the current collection zone. This work is reported in Section 4, "Current Collection Systems".

2) Development of the seal systems for the primary rotor shafts of the homopolar machines. This work is reported in Section 6, "Seal Study".

During Phase I of this program, our objectives were, 1) to review the state-of-the-art of seal technology as applicable to homopolar machines, 2) design a test apparatus capable of evaluating the performance of various seal concepts under operating conditions anticipated in homopolar machine applications.

During Phase II our objective was to develop a shaft seal system for homopolar generator applications, where the mode of operation is both unidirectional and continuous. In particular, the goal was a shaft seal for the SEGMAG generator.

In Phase III, the seal technology is to be extended to, 1) torque converter and motor applications where reversible and variable speeds are encountered , and 2) unidirectional high speed (96 m/s collector speed) generators.

## 6.1 PRIOR AND RELATED WORK

Studies performed during Phase I indicated that a tandem circumferential seal, or bore seal, was the prime candidate for satisfying the requirements imposed on the primary rotor shaft. The circumferential seal not only exhibits the ability to withstand high velocity rubbing at its primary sealing surfaces, but also the ability to provide a high degree of sealing effectiveness. Its design conserves weight and space, provides virtually unlimited shaft travel, and is easily assembled. Figure 6.1 is a schematic of this seal type.

With regard to material selection for use in these seals, care was exercised to insure that the self-lubricating composite employed retains its lubricating ability in a no-moisture, inert gas environment. Standard grades of carbon-graphite seal materials exhibit extremely poor

friction-wear characteristics in dry argon. Face seal screening tests on candidate seal materials for use in the primary rotor shaft seals of homopolar machines indicated that two polyimide matrix composites exhibit satisfactory friction-wear characteristics in the inert, no-moisture environment required for these machines. The composites contain solid lubricants, such as molybdenum disulphide, Teflon, and graphite, as fillers. Both materials were also found to be compatible with NaK at a temperature of 108°C. Seal segments suitable for use in tandem circumferential seals were fabricated from these materials.

A seal test stand was designed and constructed. Through the use of a 2:1 pulley ratio, the test stand is capable of performing experiments on various seal configurations over a 7000 rpm speed range in inert, bone-dry environments. Leakage rates, operating speed, and seal and bearing temperatures are continuously monitored. The test stand is capable of evaluating seals for shafts ranging in diameters from 2 to 6 inches.

Tandem circumferential seals were purchased for functional testing purposes as well as for use on the SEGMAG machine. Testing results on these units indicated that seal leak rates can be held to 0.02 cfm or less and that the use of carbon-graphite seal materials in these units is unsatisfactory when they are applied in dry, inert gas environments.

The test program for functional seal testing consisted of three phases:

1) Candidate seal materials were evaluated with regard to their ability to operate effectively in an inert, no-moisture environment.

2) Concurrently, these materials were evaluated with respect to their compatibility with NaK at room temperature and, where appropriate, at elevated temperature.

3) Finally, the most promising materials were fabricated into actual seals and tested extensively with respect to operating speed, runner design and material, and load pressure. The results were compared against those obtained on units employing standard carbon-graphite materials. Parameters monitored during these tests included seal wear, leakage, and operating temperature.

All face seal screening tests on candidate seal materials were completed and the results were previously reported. NaK compatibility studies on these materials were also completed and reported.

Three functional tests were performed on tandem circumferential seals designed by the Stein Seal Company. The first two experiments were performed on seals equipped with USG-67 carbon-graphite segments in
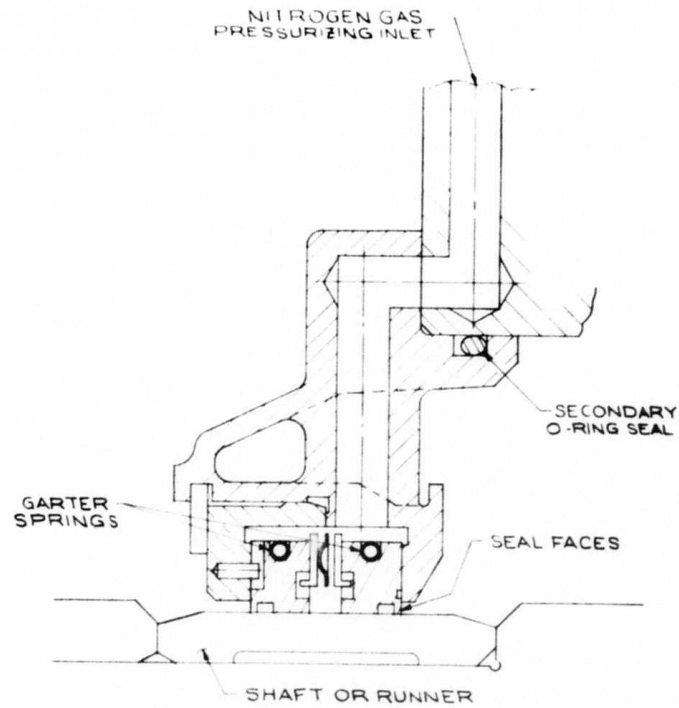
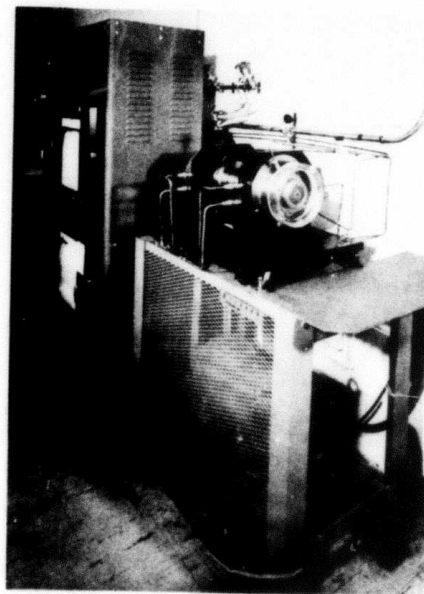Fig. 6.1 -- Schematic of typical tandem circumferential seal



Fig. 6.2 -- Tandem circumferential seal test rig

6-3

order to obtain bench mark performance data on standard seal designs. The third experiment was performed on a seal of identical design but equipped with segments fabricated from Vespel SP-211.

The first two seal tests resulted in excessive wear of the seals after 25 hours of operation in the test rig. Figure 6.2 shows this test rig.

The final test performed during this period utilized a Stein circumferential seal equipped with segments fabricated from the Vespel SP-211 polyimide-matrix composite. After an initial run-in of 10 hours, the seal was thoroughly inspected, reassembled, and then operated at 3600 rpm while being fed dry nitrogen (dew pt < - 45°C) at a feed pressure of 5 psig. A total, accumulated life of 800 hours was achieved on this seal with no segment dusting or significant wear, and with measured leak rates of 0.005 to 0.01 cfm. This seal was then inspected, reassembled and stored as a spare for SEGMAG.

The SEGMAG seals were assembled and tested for 150 hours to insure performance similar to the endurance test units.


6.2  CURRENT PROGRESS

Seal performance of the SEGMAG shaft seals was monitored during the test program. The seal leakage measured during SEGMAG operation was similar to that measured during the seal run-in period. The seals were not disassembled during SEGMAG rework since there was no evidence of damage during the test program.

A state-of-the-art review has been initiated to evaluate potential reversing seal concepts for the SMHTC shaft seals. The seals used on the SEGMAG generator are essentially a unidirectional design. The shaft seal for the SMHTC motor shaft will be designed for low leakage and wear at operating speeds from zero to 500 rpm in either direction.